TECHNO-ECONOMIC ANALYSIS OF GRID-TIED FLOATING SOLAR PV SYSTEM

Dissertation submitted to

Visvesvaraya National Institute of Technology, Nagpur

in partial fulfilment of the requirement for the award of

Degree of

Master of Technology

in

Integrated Power Systems

By

Vrushali Burele (MT23IPS003)

Under the guidance of

Dr. P. S. Kulkarni

Department of Electrical Engineering

Visvesvaraya National Institute of Technology

Nagpur- 44010 (India)

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Declaration

I, **Vrushali Burele**, hereby declare that this dissertation titled **"Techno-Economic Analysis of grid-tied Floating Solar PV System"** was carried out by me in the Department of Electrical Engineering of Visvesvaraya National Institute of Technology, Nagpur. The work is original and has not been submitted earlier, whole or in part, for the award of any degree/ diploma at this or any other Institute/ University.

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Enrollment No.: MT23IPS003

Date: 30/05/2025

Certificate

This is to certify that the dissertation titled **"Techno-Economic Analysis of grid-tied Floating Solar PV System"** is submitted by **Vrushali Burele** in partial fulfilment of the requirements for the award of the degree of Master of Technology in Integrated Power System, VNIT Nagpur. The work is comprehensive, complete, and for final evaluation.

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NON-PLAGIARISM CERTIFICATE

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ABSTRACT

In the evolving landscape of renewable energy, Floating Solar Photovoltaic (FSPV) systems have emerged as a transformative solution, addressing both energy generation and land-use challenges. By deploying photovoltaic panels over water bodies, FSPV systems leverage the natural cooling effect of water to reduce panel temperatures, enhancing efficiency and overall energy output compared to traditional ground-mounted solar photovoltaic (GSPV) systems. Additionally, FSPV installations offer numerous benefits such as minimized land use, reduced water evaporation, and decreased shading effects, making them a sustainable alternative for solar energy deployment.This study presents a comprehensive techno-economic analysis of a proposed 5 kWp FSPV system at Ambazari Lake, Nagpur. Three FSPV configurations, fixed tilt, single-axis tracking (SAT), and two-axis tracking (TAT), are evaluated using PVsyst simulation software. To further enhance system performance and energy management, a BESS is also integrated and assessed. Comparative analysis with a conventional GSPV system of the same rating is conducted to benchmark the performance metrics. Simulation results demonstrate that the FSPV system without tracking generates 0.823 MWh annually, surpassing the 0.772 MWh output of the equivalent GSPV system. Integration of BESS with FSPV enables energy storage of up to 1.131 MWh, a 15.5% increase in usable energy, allowing for improved grid responsiveness and energy availability. Among the configurations studied, the TAT system delivers the highest energy yield, producing 31.1% more energy than the fixed system and 5.3% more than SAT, though it incurs 6.25% higher system losses. Economically, despite a 28.4% increase in installation cost, TAT yields a 40.5% greater Net Present Value (NPV) and a 9.3% higher Return on Investment (ROI) over the fixed configuration. The SAT configuration also demonstrates significant promise, with 24.4% more energy production and 23.7% higher NPV compared to the fixed system. The Levelized Cost of Energy (LCOE) for the base FSPV system is calculated at Rs.3.080/kWh with a payback period of 10.6 years. These findings underscore the superior performance and economic viability of FSPV systems, particularly TAT configurations, and highlight the added value of integrating BESS in maximizing energy utilization. The study concludes that FSPV technology with tracking and storage systems presents a highly efficient and profitable approach for sustainable power generation at water-based sites like Ambazari Lake.

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NOMENCLATURE

I_s	Diode reverse saturation current (Amp)
K	Boltzman constant(=1.38X10−23 JK^{-1})
T	Temperature (Kelvin)
n	Ideality Factor (2 for Si)
K_1	Constant
V_{go}	Band gap energy (1.16eV to 1.21eV for Si)
L	Solar insolation (kW/$m2$)
δ	Declination angle (degree)
Φ	Latitude angle (degree)
ω_{st}	Sunrise angle (degree)
γ	Overall tilt factor
R_d	Tilt factor
β	Tilt angle (degree)
ρ	Reflection coefficient (0.1 to 0.7)
K_t	Clearness index (0.25 to 0.75)
H_o	Solar irradiance incident on horizontal PV module (W/m^2)
τ	Solar transmittance of the cover of the PV array (%)
α	Solar absorption PV array (%)
G_T	Insolation striking the solar panel (kWh/m^2)
η_c	Efficiency of the solar panel (%),
U_T	Coefficient of heat transfer to the surrounding (kWh/m^2°c),
T_c	Cell temperature (°C)
T_a	Ambient temperature (°C)
r	Discount rate (%)

N	Plant's lifetime (years)
E_{FPV}	Total energy output till the project lifetime (kWh)
K	Degradation rate (%/ year)
C_T	Cash flow for a particular year
C_o	Total investment (Rs)
Y_r	Reference System Yield (kWh/kWp)
Y_a	Array Yield (kWh/kWp)
Y_f	Final Yield (kWh/kWp)
L_c	Collection Loss (%)
L_s	System Loss (%)
E_{FPV}	Energy output from PV modules (Wh)
G	Reference Irradiance (W/ m^2)
A	Area of PV module (m^2)
η	Efficiency of PV module (%)
H_{at}	Incident solar irradiation of PV module (kWh/m^2/day)
A	Area of PV module (m^2)
N	Number of PV modules
β_t	Thermal coefficient of PV module(%/°C)
T_{cell}	PV cell Temperature (°C)
T_{ref}	Reference Temperature (°C)

ABBREVIATIONS

JNNSM	Jawaharlal Nehru National Solar Mission
FSPV	Floating Solar Photovoltaic
GSPV	Ground mounted Solar Photovoltaic
SAT	Single Axis Tracking
TAT	Two Axis Tracking
HDPE	High Density Poly-Ethylene
LCOE	Levelized Cost of Electricity
PR	Performance Ratio
CUF	Capital Utilization Factor
LCE	Life Cycle Emission
LCC	Life Cycle Cost
ROI	Return on Investment
NPV	Net Present Value
CERC	Central Electricity Regulatory Commission
BESS	Battery Energy Storage System

LIST OF PUBLICATIONS

1. Vrushali Burele and P. S. Kulkarni, "Techno-Economic Analysis of proposed 5kWp Floating Solar Plant with Battery Energy Storage System at Ambazari Lake, Nagpur, India", Proceedings of International Conference on Power, Control and Computing Technologies (ICPC2T), NIT Raipur ,2025, doi: 10.1109/ICPC2T63847.2025.10958586.
2. Vrushali Burele, G. Mamatha, and P. S. Kulkarni, "Techno-Economic Analysis of proposed 5kWp Tracking Type FSPV Systems at Ambazari Lake, Nagpur." Proceedings of International Conference on Sustainable Energy and Future Electric Transportation (SEFET), MNIT Jaipur, (9 to 11 July 2025). (ACCEPTED)

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CHAPTER 1: INTRODUCTION

1.1 Background

Floating solar photovoltaic (FPV) systems have emerged as an innovative and sustainable solution to address land constraints while enhancing renewable energy generation. The concept was first demonstrated in 2007 with a 175 kW pilot installation in Aichi, Japan, mounted on an irrigation reservoir. Early adoption was driven by countries with limited available land, such as Japan and South Korea, where floating solar efficiently utilized underused water bodies. By 2015, the global FPV capacity had reached a modest 50 MW, but the subsequent years witnessed exponential growth as the technology proved its viability. Between 2016 and 2020, large-scale FPV projects began to dominate, particularly in China, which emerged as the global leader with the 150 MW Anhui plant (2017), the largest at the time. The World Bank (2019) estimated that if just 1% of man-made freshwater reservoirs were used for FPV installations, the global potential could exceed 400 GW, surpassing early market projections. By 2020, cumulative installed capacity had crossed 2 GW, with notable contributions from India (e.g., the 100 MW Kayamkulam project in Kerala) and Southeast Asian nations like Thailand and Vietnam. The period 2021–2025 marked a shift toward hybrid energy systems, where floating solar was integrated with existing hydropower plants to optimize energy output and grid stability. The National Renewable Energy Laboratory (NREL, 2021) highlighted that such hybrid configurations could significantly enhance efficiency, as hydropower reservoirs provided ideal conditions for FPV deployment. Meanwhile, Europe saw increasing adoption, with the Netherlands targeting 3 GW of floating solar by 2030, and France experimenting with solar-over-canal projects to reduce water evaporation.

Technological advancements played a crucial role in this expansion. Innovations in flotation materials (e.g., high-density polyethylene structures), anti-corrosive designs, and automated cleaning systems improved system durability and reduced maintenance costs. Additionally, research indicated that water-cooling effects could enhance solar panel efficiency by 5–10% compared to land-based systems (IEA-PVPS, 2020). Despite rapid growth, challenges such as higher initial costs, environmental concerns (e.g., aquatic

ecosystem impact), and site-specific design requirements posed hurdles. However, with governments introducing policy incentives (e.g., India's 30 GW FPV target by 2030) and private investments rising, the market is projected to exceed 4.8 GW by 2025 (Wood Mackenzie, 2022). Looking ahead, floating solar is expected to play a pivotal role in the global renewable energy transition, particularly in regions with dense populations and limited land availability. Fig.1.1 shows the source-wise contribution to total installed electricity generation capacity, and Fig.1.2 shows the source-wise contribution to electricity generation.

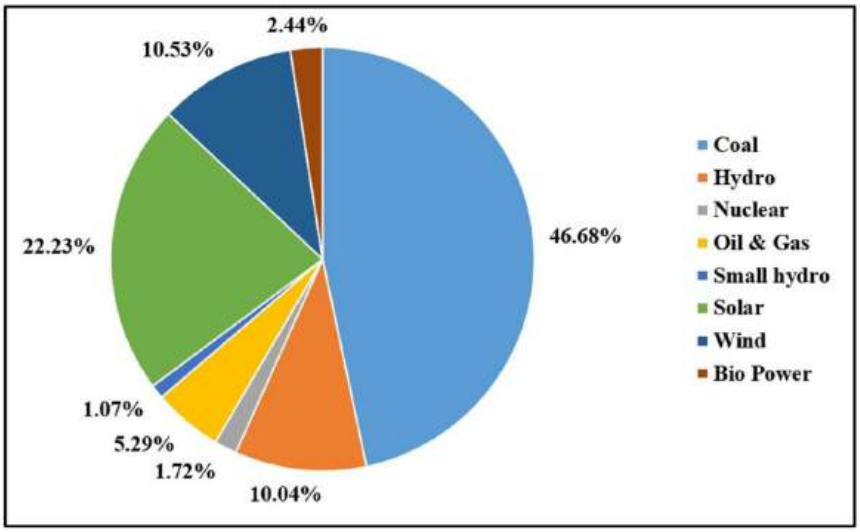

Fig. 1.1:Source-wise electricity installed capacity (as on 31 March 2025) [3]

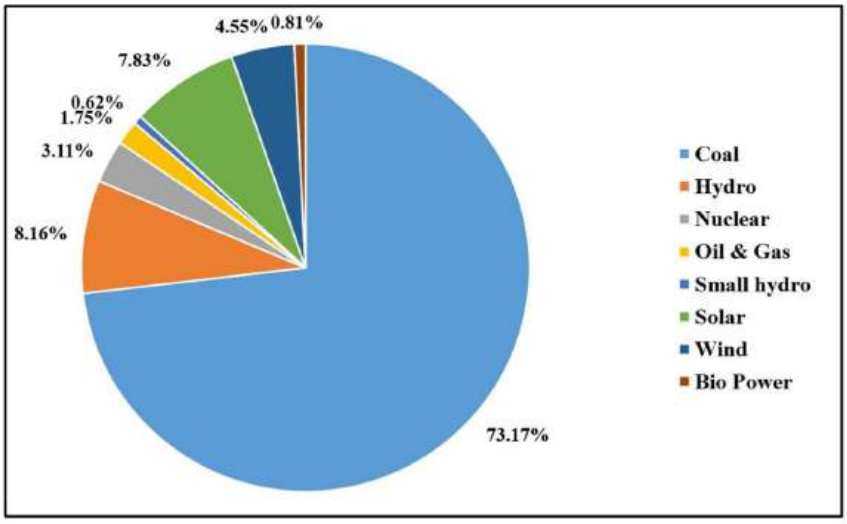

Fig. 1.2:Source-wise electricity generation (as on 31 March 2025) [3]

1.2 Floating Solar PV System

1.2.1 Overview

Floating solar, also referred to as floating photovoltaic (FSPV) systems, involves deploying solar panels over water surfaces such as lakes, reservoirs, or ponds. This innovative solution effectively utilizes unused water bodies to produce clean energy while preserving valuable land resources. The cooling properties of water beneath the panels help improve their performance when compared to conventional ground-mounted systems. Moreover, floating solar systems can minimize water loss through evaporation, which is particularly advantageous in dry regions [1]. They are especially appropriate for areas with high solar potential but restricted land availability. Fig. 1.3 illustrates the availability of water bodies across various Indian states, and Fig. 1.4 depicts the necessary area of water bodies evaluated for FSPV feasibility in India.

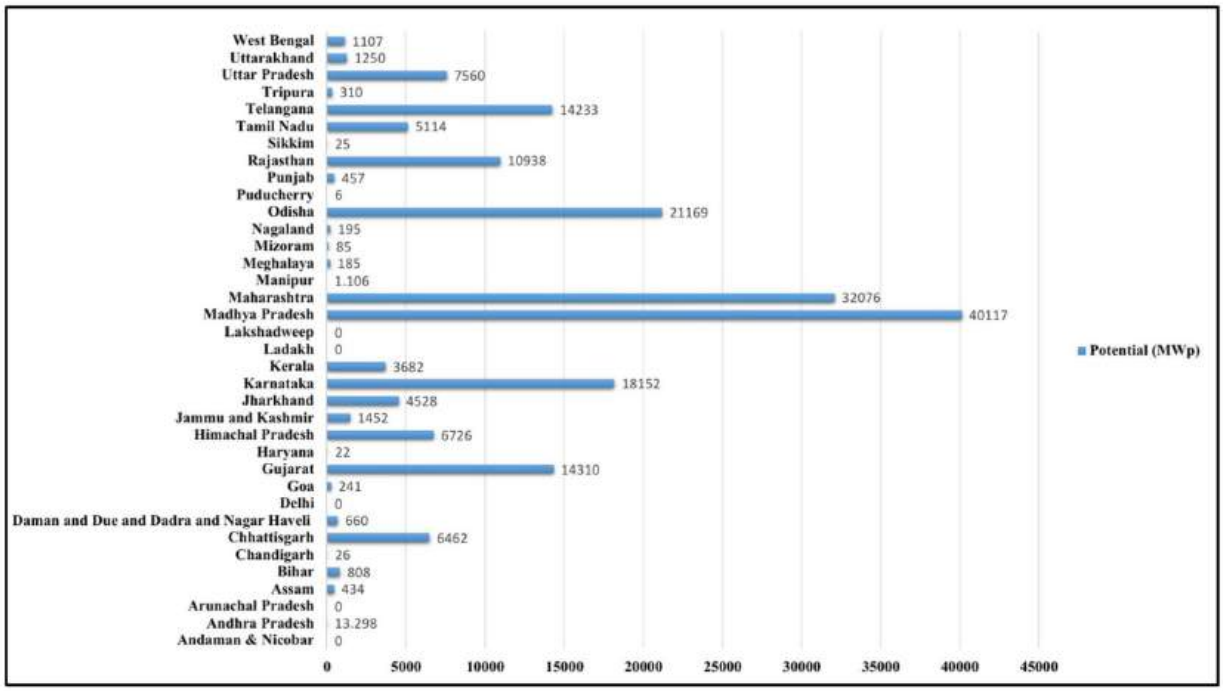

Fig. 1.3: FSPV potential of India [3]

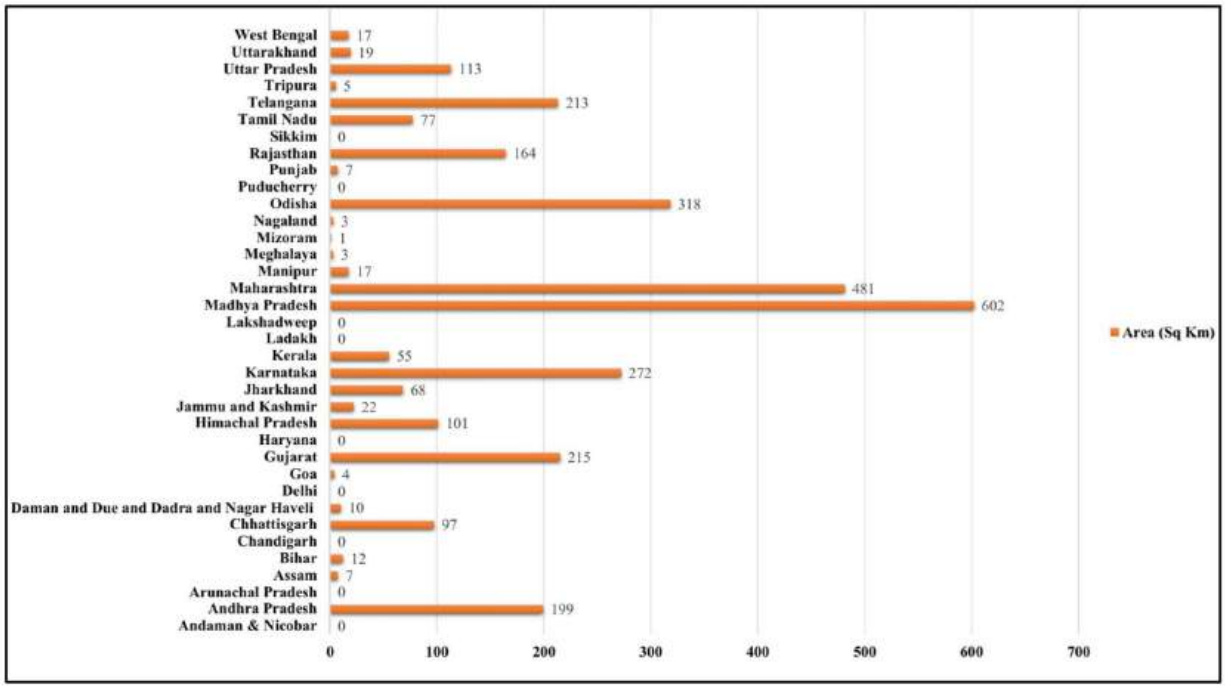

Fig. 1.4: Area of water bodies considered for assessing India's FSPV potential. [3]

1.2.2 Components of Floating Solar PV System

A Floating Solar Photovoltaic (FSPV) plant is a solar energy system where solar panels are mounted on floating platforms placed over a water body like a lake, pond, or reservoir, instead of being installed on land. While the overall system design closely resembles conventional land-based solar PV systems, it includes specific adaptations to enable floating functionality. The main components, such as PV modules, inverters, combiner boxes, and lightning protection systems, are mounted on a floating platform, typically constructed from materials like HDPE (high-density polyethylene), FRP (fiber-reinforced plastic), or metal frameworks. The entire floating structure is secured using anchoring and mooring systems to maintain stability and position [2]. Fig.1.5 illustrates a typical schematic layout of an FSPV system. A detailed breakdown of the individual components of the floating solar setup is provided below:

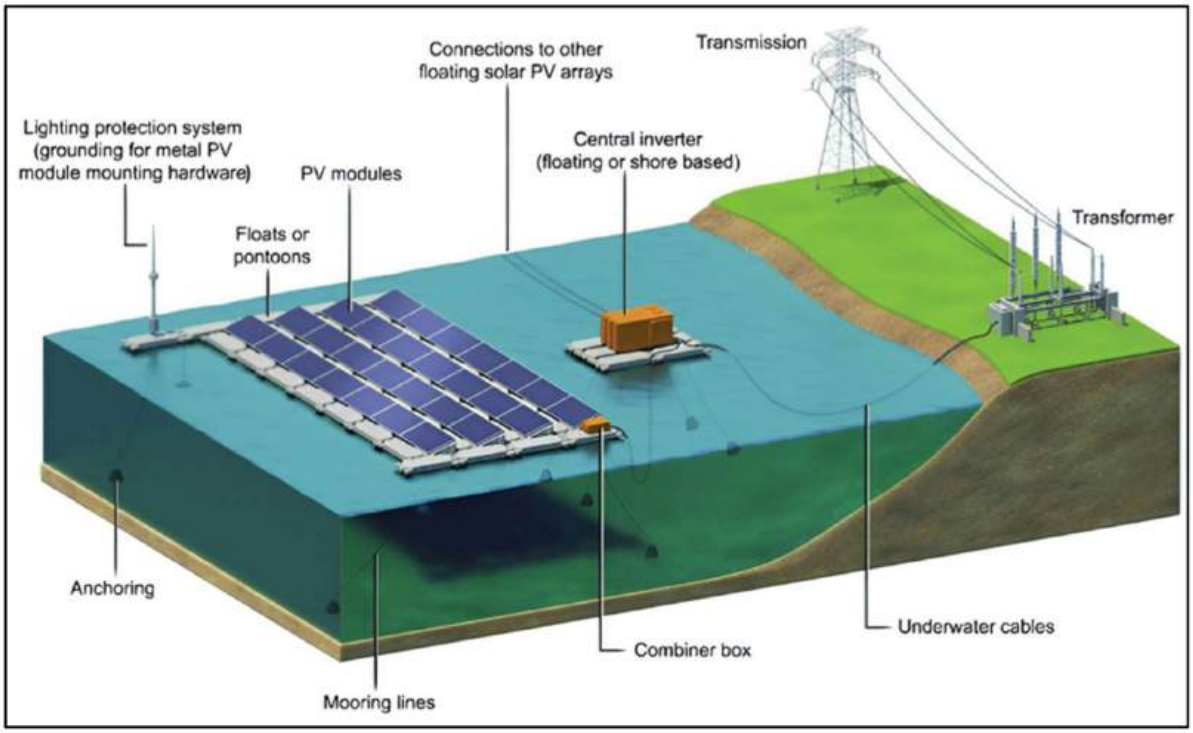

Fig. 1.5: Schematic diagram of FSPV system. [3]

- **PV Modules:** Photovoltaic modules are the main component of a Floating Solar Photovoltaic (FSPV) system. Like conventional solar installations, these can be polycrystalline, monocrystalline, or thin-film types. The selection of module technology depends on various site-specific factors such as available space, cost constraints, ambient humidity levels, and the characteristics of the water body where the system is to be deployed.

- **Inverters:** The direct current (DC) electricity generated by the PV modules is collected through combiner boxes and then sent to inverters for conversion into alternating current (AC). Similar to ground-mounted solar systems, FSPV setups can use either string inverters or central inverters, depending on system requirements. The placement of inverters either on a dedicated floating structure or onshore depends on the plant's capacity and proximity to the shoreline. For small-scale installations, placing inverters on land is typically sufficient. However, in larger systems, installing

inverters on floating platforms can help reduce transmission losses due to long cable runs. Each option has advantages and limitations, and the choice should be based on careful technical and economic evaluation.

- **Floating Platform:** Floatation devices, commonly called floaters, serve multiple critical functions in a Floating Photovoltaic (FPV) system. They support and secure essential components such as solar PV modules, combiner boxes, cables, string inverters, and transformers, while also providing the necessary buoyancy to keep the system afloat and stable. These devices are designed to maintain the plant's structural integrity under various environmental conditions throughout its operational life, including during assembly, installation, and routine operation.

  The design and structure of floaters vary based on the type and magnitude of the load they are intended to carry. Generally, flotation devices fall into two main categories: those that support PV modules and electrical components (like combiner boxes and inverters), and those that assist with structural stability or cable management.

  Floaters can be constructed from a range of materials, including Ferro cement, steel, aluminum, thermoplastics, expanded polystyrene (EPS), and cement-based composites. There are three main types of flotation devices used in commercial FPV systems:

  1. **Pure Floats:** These are standalone units where PV modules are directly mounted onto the float itself. Each unit can support one or multiple modules, and the structure integrates both the load-bearing and buoyancy functions.
  2. **Modular Raft:** This design separates the structural frame from the buoyant element. Typically, the frame, made from corrosion-resistant metal, supports the PV modules, while thermoplastic pontoons or floats provide the necessary buoyancy to keep the structure afloat.
  3. **Membrane Floats:** Similar in concept to modular rafts, membrane-based floaters use a reinforced membrane instead of a rigid structural frame to support the PV modules. Buoyancy is achieved using additional elements like tubular rings or sealed chambers.

Fig. 1.6 illustrates the various types of floats commonly employed in contemporary Floating Solar Photovoltaic (FSPV) systems.

Fig. 1.6: Types of Floats [3]

- **Mooring system:** Mooring lines in Floating Solar Photovoltaic (FSPV) systems link the floating platform to anchors and are typically made of steel chains, wire ropes, or synthetic ropes. These can be used alone or in combination, forming either catenary or taut mooring systems. For example, a catenary system may use a heavy chain on the reservoir bed for stability, synthetic rope for flexibility, and steel wire rope near the surface for abrasion resistance. Chains are durable and cost-effective but are limited by depth due to their weight, and must be paired with equally strong hardware for safe and effective performance.

- **Anchors system:** The selection of an anchor for a Floating Photovoltaic (FPV) system depends on factors such as the required load-bearing capacity and the properties of the reservoir bed. The offshore industry, including wind and oil & gas sectors, has developed various anchor solutions like pile, deadweight, drag, and plate anchors, each tested for specific conditions. The effectiveness of these anchors is determined by their design and the soil characteristics. For instance, a pile anchor might be chosen over a deadweight anchor when high uplift resistance is needed but weight restrictions apply. Site-specific challenges may also dictate whether simple, innovative, cost-effective, or more expensive designs and installation methods are necessary. For FPV systems, which typically operate in shallow waters and cover large surface areas, the commonly preferred anchor types include:

1. **Gravity / Deadweight Anchor-** This anchor derives its holding capacity primarily from its own weight, supplemented by friction between the anchor and the reservoir bed. Materials like concrete and steel are often used in its construction.
2. **Pile / Driven Pile / Helical Pile Anchor-** Consisting of a hollow steel pipe, sometimes with a helix, this anchor is installed using methods such as piling hammers, vibrators, or hydraulic torque motors. Its load-bearing capacity comes from soil friction along the pile and lateral soil resistance, enabling it to handle both horizontal and vertical loads.
3. **Drag Embedment Anchor-** A widely available, off-the-shelf option, this anchor is designed to penetrate the reservoir bed partially or fully. Its holding capacity relies on the soil resistance in front of it. While effective for large horizontal loads, it is less suitable for significant vertical loads.

Fig. 1.7 shows the types of Anchors [a] dependent on characteristics of reservoir bed (soil composition and type); [b] reservoir bed topography; [c] loading direction; and [d] lateral load range.

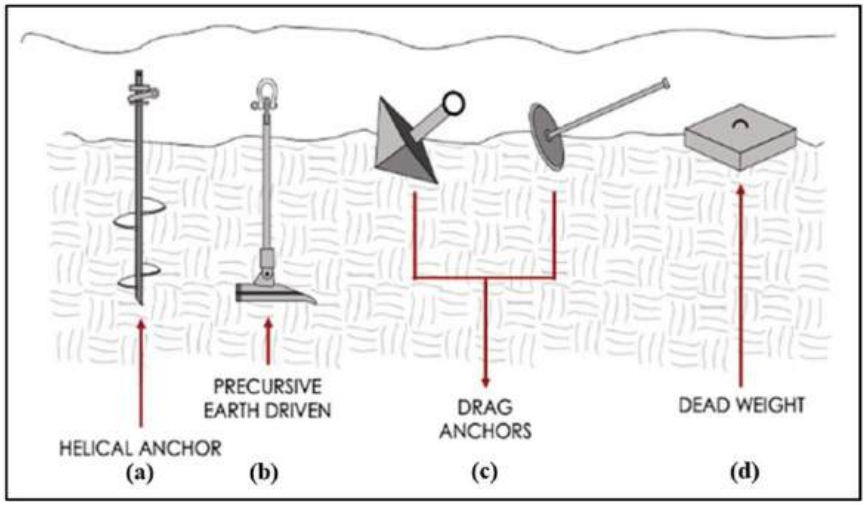

Fig. 1.7: Types of Anchors [3]

- **Cabling:** Effective cable routing and management are critical in floating solar photovoltaic (FSPV) installations. Unlike land-based PV systems, floating platforms are subject to dynamic environmental conditions, such as wind forces and varying

water levels, which cause continuous movement. This movement alters the cable lengths, necessitating strategic planning to ensure durability and functionality.

To accommodate the shifting of the floating structure, extra cable length in the form of slack must be included. Failure to do so can result in excessive tension, leading to cable snapping or damage. In addition to accommodating movement, factors such as the cable's voltage rating, current-carrying capacity, and energy losses also play a key role in determining the appropriate cable size.

Two primary methods exist for laying cables in FSPV projects: routing along floating pontoons on the water's surface or using underwater (submarine) cables. While submarine cables provide robust protection, they are typically more expensive than surface-mounted alternatives.

Several considerations are essential for designing the cable layout in an FSPV plant:

i. Size and layout of the project area
ii. Distance between the floating array and the shore
iii. Locations of electrical components like inverters and transformers
iv. Water quality, which can affect material corrosion and insulation longevity
v. Seasonal or environmental variations in water level

1.2.3 Advantages and disadvantages of the Floating Solar PV system

- The advantages of the floating solar PV system are as follows [4]:

i. **Improved energy efficiency from natural cooling:** Solar panels on floating platforms operate at lower temperatures thanks to cooler air temperatures near water and higher wind activity over water surfaces. This natural cooling effect, caused by evaporation and increased airflow, helps reduce the thermal load on PV modules, resulting in higher energy generation compared to traditional land-based installations.

ii. **Conservation of land resources:** Since FSPV systems are installed on water bodies, they significantly reduce or eliminate the need for land. This makes them especially valuable in densely populated or agriculturally important areas, where land availability is limited and costly, such as in many regions of India.

iii. **Lower water loss through evaporation:** Covering a water body with solar panels limits exposure to sunlight and reduces wind-driven surface disturbance, both of which are major contributors to water evaporation. In areas with high temperatures and low rainfall, this feature is particularly useful for preserving vital water resources. As per data from India's Central Water Commission, annual evaporation losses can range from 150 to 300 cm per square kilometer.

iv. **Integration with Existing Power Infrastructure:** Many reservoirs already support activities like irrigation, municipal water supply, or hydroelectric generation and are often connected to the grid. Installing FSPV systems on such sites allows for the use of pre-existing electrical infrastructure, cutting down on the cost and effort required for new grid connections.

v. **Hydropower and Solar Complementarity:** Hydroelectric plants often generate less power during dry seasons, just when solar energy production peaks due to higher sunlight. Pairing FSPV with hydroelectric facilities enables consistent year-round power output. This dual setup also allows for effective energy management, using solar during the day and hydro at night. However, designing FSPV arrays on reservoirs with varying water levels can be technically challenging and requires careful engineering.

vi. **Possible Reduction in Algal Blooms:** The shading effect of floating panels can lower light intensity and surface temperature of water, which may suppress the growth of algae. While this may offer ecological advantages, the long-term impacts of FSPV deployment on aquatic ecosystems still need further study.

vii. **Revenue Potential for Water Body Owners:** FSPV installations can generate financial returns for water body owners, either through reduced electricity costs when used for self-consumption or through income from selling excess power to the grid. This transforms idle water surfaces into economically productive spaces.

viii. **Lower Dust and Dirt Accumulation:** Compared to land-based systems, floating solar panels are exposed to less airborne dust because winds across water surfaces tend to carry fewer particulates. This leads to reduced soiling and helps maintain panel efficiency.

ix. **Easy Access to Cleaning Water:** Since FSPV systems are already located on water, cleaning the modules is more convenient. However, the water used for cleaning must comply with the quality standards specified by PV manufacturers to avoid damage.

x. **Quick and Efficient Installation Process:** FSPV plants are simpler to install than ground-mounted systems. This is because of:

   a. No need for land grading or civil foundations.
   b. Use of modular floating units that are easy to assemble.
   c. Rows of floats can be connected onshore and pushed into the water sequentially.
   d. The completed structure can be maneuvered into position using small boats.

- The disadvantages of a floating PV system are as follows [4]:
  a. Water quality may be affected by materials like HDPE and silicone used in the system.
  b. Submerged electrical cables pose risks of electric leakage and harm to aquatic life.
  c. Key environmental factors such as water depth, flow, oxygen levels, and aquatic species are often not thoroughly studied.
  d. Long-term exposure to humidity, salinity, and wind can lead to corrosion, biofouling, and increased maintenance costs.
  e. FSPV installations may disrupt the natural behavior of surface-diving and migratory birds.
  f. Shading from the panels can reduce water temperature and disturb the dissolved oxygen balance.
  g. Reduced sunlight may hinder natural chemical processes, leading to higher organic carbon levels and increased water treatment costs.
  h. Lack of sunlight can affect phototrophic microbes, disrupting nutrient cycles and aquatic ecosystem stability.

1.2.4 Challenges of the FSPV plant

- Challenges in implementing and designing guidelines are as follows [4]:
  a. **Lack of Technical Standards and Design Guidelines:** FSPV technology is still emerging, and currently, there are no well-established standards or protocols for its implementation. Unlike ground-mounted PV systems, FSPV setups require specialized design considerations for floating structures, mooring systems, and anchoring mechanisms. To ensure long-term durability, especially under harsh climatic conditions, and to protect biodiversity, it is essential to develop component-specific guidelines and robust technical standards.
  b. **Inadequate Water Body Data Availability:** Comprehensive datasets on water bodies are generally lacking. Key information—such as surface area, seasonal water level changes, historical variations, meteorological profiles, and ecological data, is critical for evaluating site feasibility and accurately assessing the potential of FSPV projects. The absence of such data hampers effective planning and design.
  c. **Concerns over Component Safety and Durability:** FSPV installations are consistently exposed to extreme environmental conditions like high humidity, salinity, and strong winds. This continuous exposure increases the risk of degradation in electrical and electronic components, making long-term operation and maintenance more complex and potentially costly than land-based systems.
  d. **Limited Local Manufacturing of Specialized Components:** Many essential parts of an FSPV plant—including floating platforms and mooring systems are not commonly manufactured domestically. This increases dependency on imports or customized fabrication, raising cost and logistical challenges, especially when scaling up projects.
  e. **Absence of Bathymetric Survey Data:** Understanding the underwater topography of a reservoir or lake through bathymetric (hydrographic) surveys is essential for assessing the site's technical and commercial viability. Inadequate or missing bathymetry data can lead to flawed design decisions, increasing the risk of structural failure and reducing the overall effectiveness of the FSPV system.

1.2.5 Global scenario of Floating Solar Plant

By 2025, floating solar photovoltaic (FSPV) technology is expected to gain substantial global traction as a viable and scalable alternative, addressing the expanding global need for eco-friendly power sources amid rising land scarcity. According to the International Renewable Energy Agency (IRENA), the total global solar PV capacity has surpassed 1,500 GW, with floating solar contributing a rising share through its deployment on reservoirs, lakes, and other water bodies [4]. Countries such as China, South Korea, India, and Indonesia have emerged as leaders in FSPV adoption, driven by large-scale government programs and the advantage of coupling solar with hydropower infrastructure. Notable developments include China's 650 MW plant in Anhui and India's 600 MW Omkareshwar project, with several multi-gigawatt initiatives underway.

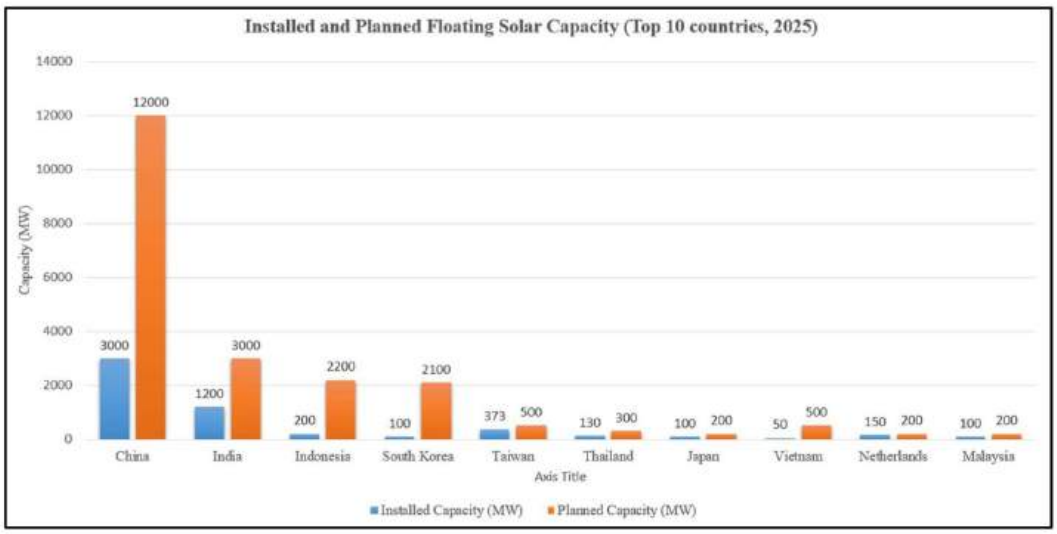

Fig 1.8: Installed and Planned Floating Solar Capacity of top 10 countries (Till 2025)

Looking ahead, between 2025 and 2030, the floating solar market is expected to grow substantially, with global capacity additions projected to exceed 6–10 GW annually [5]. The World Bank estimates that even utilizing a small fraction of man-made water surfaces could generate over 4,000 GW of power globally [3]. Southeast Asia, in particular, is set to become a hotspot for floating solar due to its abundant inland water resources and high solar irradiance. Continued advancements in modular designs, anchoring systems, and hybrid floating solar-hydro projects are expected to reduce costs and enhance efficiency, supporting broader deployment across Africa, Latin America, and Europe as well [6]. The above fig 1.8 provides

a comparative view of the top 10 countries by their installed and planned floating solar capacities as of 2025, reflecting both current leadership and future readiness in this transformative sector.

1.2.6 Floating solar plants in India

Table 1.1 represents operational and upcoming FSPV plants in India [32, 33, 34, 35 and 36].

Table 1.1: Floating solar projects that are operational and upcoming, as of 2025

Project Name	Capacity	Location	Commissioned	Developer
Rihand Floating Solar Plant	150 MW	Sonbhadra, Uttar Pradesh	Under construction	NTPC
Omkareshwar Floating Solar Project	600 MW	Khandwa, Madhya Pradesh	Under construction	Rewa Ultra Mega Solar Ltd (RUMSL)
Chandigarh Floating Solar Plant	2 MW	Chandigarh	2023 Operational	Hartek Solar / CREST
NTPC Ramagundam Floating Solar Plant	100 MW	Ramagundam, Telangana	2022 Operational	NTPC
Kayamkulam Floating Solar Project	92 MW	Kayamkulam, Kerala	2022 Operational	NTPC
NTPC Haripad Floating Solar Plant	92 MW	Haripad, Kerala	2022 Operational	NTPC
Kawas Floating Solar Plant	23 MW	Surat, Gujarat	2022 Operational	NTPC
Auraiya Floating Solar Plant	20 MW	Auraiya, Uttar Pradesh	2022 Operational	NTPC
Meghadri Gedda Reservoir Floating Solar	3 MW	Visakhapatnam, Andhra Pradesh	2022 Operational	GVMC / ADB-funded
Simhadri Floating Solar Project	25 MW	Visakhapatnam, Andhra Pradesh	2021 Operational	NTPC
Mudasarlova Reservoir Floating Solar	2 MW	Visakhapatnam, Andhra Pradesh	2018 Operational	Greater Visakhapatnam Municipal Corporation

1.3 Literature Survey

Many researchers have studied the techno-economic analysis of floating solar PV systems. Niccolai *et al.* provided an overview of recent trends in FSPV systems compared to GSPV systems from 2013 to 2023. Further, they presented economic analysis, remote control maintenance, and operation methodologies of FSPV [5]. Madhubabu and Rao reviewed the technology and methods to install a floating solar PV (FSPV) system [6]. Gurfude *et al.* performed a techno-economic analysis of a proposed 1MWp FSPV at Ambazari Lake, Nagpur [7]. Snehith and Kulkarni have proposed a 10 MWp FSPV at Nagarjuna Sagar dam, Telangana, and carried out a technical analysis. The authors concluded that the proposed FSPV generates 3.18% more energy than GSPV plants and saves 919 million liters of water from evaporation annually [8]. Later, Snehith and Kulkarni performed economic analysis. The authors concluded that the levelized tariff for FSPV plants is 21% higher than that of GSPV plants due to increased capital and operational costs. Despite this, the economic benefits of both types of plants are nearly the same, although rising land costs are driving up the investment and levelized tariff for GSPV plants [9]. Subsequently, Patil *et al.* proposed a techno-economic analysis of 10kWp FSPV at Koyana Dam, Maharashtra. The authors conclude that single-axis tracking produces 18-21% more energy, while two-axis tracking generates 27-30% more energy compared to a fixed-mounted FSPV plant. The FSPV plant represents an optimal solution for reducing fossil fuel usage and, in turn, addressing the impacts of climate change [10].Mamatha and Kulkarni performed feasibility analysis of the FSPV plant at Srisailam in Andhra Pradesh. The authors proposed a 5MWp FSPV plant and concluded that FSPV produces a 4.8% increase in capacity and results in a 5.45% reduction in carbon emissions annually compared to the GSPV Plant [11]. Mittal *et al.* did the energy calculations and comparison of a 1MW GSPV and 1MW FSPV plant in Jodhpur. The authors concluded that the FSPV system demonstrates a 2.48% increase in annual energy production, accompanied by a 14.56% reduction in module temperature [12]. Ramzan and Jamil carried out comparative analysis of FSPV and GSPV at Wullar lake, Jammu and Kashmir. FSPV generates an extra 44.5 MWh of energy annually and LCOE for FSPV decreases as compared to GSPV [13]. The FSPV with BESS can improve the performance of the plant. The BESS stores excess energy generated during the day to stabilize fluctuations, helping the system

manage daily demand and storage more effectively. An integrated system can enhance power transmission, reduce operating costs, minimize land use, and decrease evaporation [14]. Yang and Xiao reviewed the sustainable growth of solar photovoltaic tracking technology, emphasizing its present issues, upcoming developments, and contribution to the advancement of clean energy via increased productivity, creativity, and digital integration [15]. A study by Abhinav *et al.* on solar panels with single-axis tracking and floating trackers showed increased efficiency over fixed tilt panels. Power output rose by 2.81% to 45.61%, and daily energy production improved by 17.92% to 19.44% [16]. Economic analysis revealed a 34.93% gain for tracking panels and 45.55% for floating panels with trackers. Gurfude and Kulkarni examined the performance of tracking systems in an FSPV plant in Nagpur, and concluded that when compared to fixed-tilt FSPV systems, 1-axis tracking technology produces 18–21% more energy. Moreover, a 2-axis tracking system on the FSPV plant delivers 25-30% more energy compared to a fixed-tilt FSPV system [17].

Hammoumi *et al.* reviewed optimization of PV power using solar tracking and FSPV. Further authors stated that solar tracking systems significantly enhance energy generation, capturing 10%–50% more solar energy than fixed-angle PV systems [18]. Integrating a tracker with floating PV systems can further boost efficiency. Thus, developing and implementing a tracking-based floating PV system presents a promising approach. Avasthi *et al.* study evaluates solar plant performance, showing Dual Axis Tracking (DAT) outperforms Fixed Tilted (FT) and Horizontal Single Axis Tracking (HSAT), generating 27.08% more energy [19]. DAT achieved up to 21.32% higher yields, with efficiency ranging from 14.97% to 16.56%. Findings highlight DAT's superiority for optimizing floating solar PV systems.

Rifansyah and Hakam carried out the study using RETScreen technology to assess the techno-economic feasibility of the 145 MW FPV project [20]. The study highlights the notable difference in PV tariffs between Indonesia and countries like Nigeria and Pakistan. Despite the lower tariff, the Cirata (located in Indonesia) floating solar PV plant achieves a reduced electricity cost, making it more cost-effective than ground-mounted solar PV systems. A study comparing pivotless tracking and fixed-type solar PV systems was conducted by Jee *et al.* at the Irwol Reservoir in Suwon, South Korea, with performance monitored from May 2019 to June 2020 [21]. Results showed that the tracking-type system produced about 14%

more energy overall, peaking at a 25.63% increase in May and dropping to a 3% gain during winter. Akgul *et al.* study presented a method to optimize tilt angle for fixed panels and compared it to tracking systems [22]. The results show that optimally tilted panels increase daily solar radiation by 9.33–12.90%, with one-axis and two-axis tracking systems improving radiation capture by 28.48–33.09% and 32.41–37.12%, respectively, compared to fixed systems, and the method can be applied globally. Marcos *et al.* study evaluates energy gains from dual-axis sun-tracking PV panels in Manta, Ecuador [23]. Using an IoT-based system with Raspberry Pi3 and Arduino, results show a 19.62% increase over static PV and 8.62% more than one-axis tracking in a similar region.

1.4 Aims and Objectives of the Study

The objectives of this study are listed below:

1. To study the design of the proposed 5kWp FSPV plant at Ambazari Lake, Nagpur.
2. To perform techno-economic analysis of the proposed 5kWp FSPV and compare it with the Ground Mounted Solar PV (GSPV) system of the same rating.
3. To study Battery Energy Storage System (BESS) and perform techno-economic analysis of proposed 5kWp FSPV with BESS (i.e., Lithium-ion battery)
4. To perform techno-economic analysis of the proposed 5kWp FSPV with tracking systems, and compare it with the FSPV and the GSPV systems.
5. To perform a comparative analysis of the proposed system of different capacities (i.e., 5MW system)

1.5 Dissertation Outline

This dissertation is organized as follows: Chapter 2 includes the PV cell mathematical model, the design, techno-economic analysis of the proposed 5kWp FSPV plant at Ambazari Lake, Maharashtra. Chapter 3 presents the comparative analysis of FSPV with tracking types of systems (i.e., Single Axis Tracking and Two Axis Tracking).Chapter 4 describes the analysis of FSPV with Battery Energy Storage System (BESS). Chapter 5 presents the comparison of techno-economic parameters of FSPV plants of different capacities. Chapter 6 summarizes the conclusions and gives direction for future work.

CHAPTER 2: TECHNO-ECONOMIC ANALYSIS OF THE PROPOSED 5kWp GRID-TIED FSPV PLANT AT AMBAZARI LAKE, MAHARASHTRA.

2.1. Introduction: PV cell and its mathematical model

The equivalent circuit of a PV cell primarily consists of a current source in parallel with a diode, representing the ideal PV characteristics. The model is enhanced by adding series resistance (Rs) and shunt resistance (Rp) to represent internal losses and leakage currents. The series resistance reflects losses due to internal connections and material properties, while the shunt resistance represents leakage currents across the cell. This comprehensive configuration, illustrated in Fig.2.1, allows for more accurate performance analysis under varying environmental and loading conditions [2].

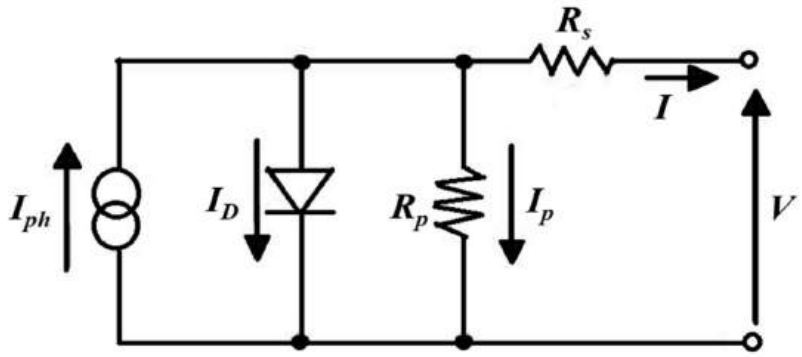

Fig. 2.1: Equivalent circuit of PV cell

Applying Kirchhoff's current law at the principal node, we get,

$$I_{ph} = I_D + I_p + I \quad (2.1)$$

Rearranging the above equation in terms of the output current I and applying the KVL at output side,

$$I = I_{ph} - I_D - \left(\frac{V+(I*R_s)}{R_p}\right) \quad (2.2)$$

We know the diode equation,

$$I_D = I_s * (e^{\left(\frac{V+(I*R_S)}{n*V_t}\right)} - 1)$$

(2.3)

Thermal voltage V_t and diode reverse saturation current I_o can be written as,

$$V_t = \frac{KT}{q} = \frac{T}{11600} \quad (2.4)$$

$$I_o = K_1 * T^m * e^{\frac{V_{go}}{nV_t}}$$

(2.5)

Where,

Is = Diode reverse saturation current in amperes

K = Boltzman constant=1.38X10−23 $JK-1$

T = Temperature in Kelvin

n = Ideality Factor (2 for Si)

K_1 = Constant

V_{go} = Band gap energy (1.16eV to 1.21eV for Si)

m = temperature exponent constant (1.5 for Si)

Combining (2.2) and (2.3), we get the output current equation as,

$$I = I_p - I_s * \left(e^{\left(\frac{V+(I*R_S)}{n*V_t}\right)} - 1\right) - \left(\frac{V+(I*R_S)}{R_p}\right) \quad (2.6)$$

2.2. Design of proposed 5kWp FSPV plant

2.2.1 Site Details

The proposed 5kWp FSPV plant is to be installed on the Ambazari Lake in Nagpur, Maharashtra, India. And the proposed 5kWp GSPV plant is to be installed in the VNIT, Nagpur, Maharashtra, India. The coordinates of the FSPV and GSPV plants are 21.1287° N, 79.0405° E and 21.1232° N, 79.0515° E respectively. Fig 2.2 shows satellite view of Ambazari Lake. In this solar panels are placed with a 21° fixed tilt angle to get maximum solar irradiation. The meteorological data was obtained from PVsyst software. It is the biggest lake in the city and one of Nagpur's eleven lakes. For more than 30 years, Nagpur received its water from the lake.

Fig 2.2: Ambazari Lake (Satellite view) (source Google earth)

2.2.2 Methodology in PVsyst

Fig 2.3 shows the methodology block diagram illustrating the workflow followed in PVsyst Software [28].

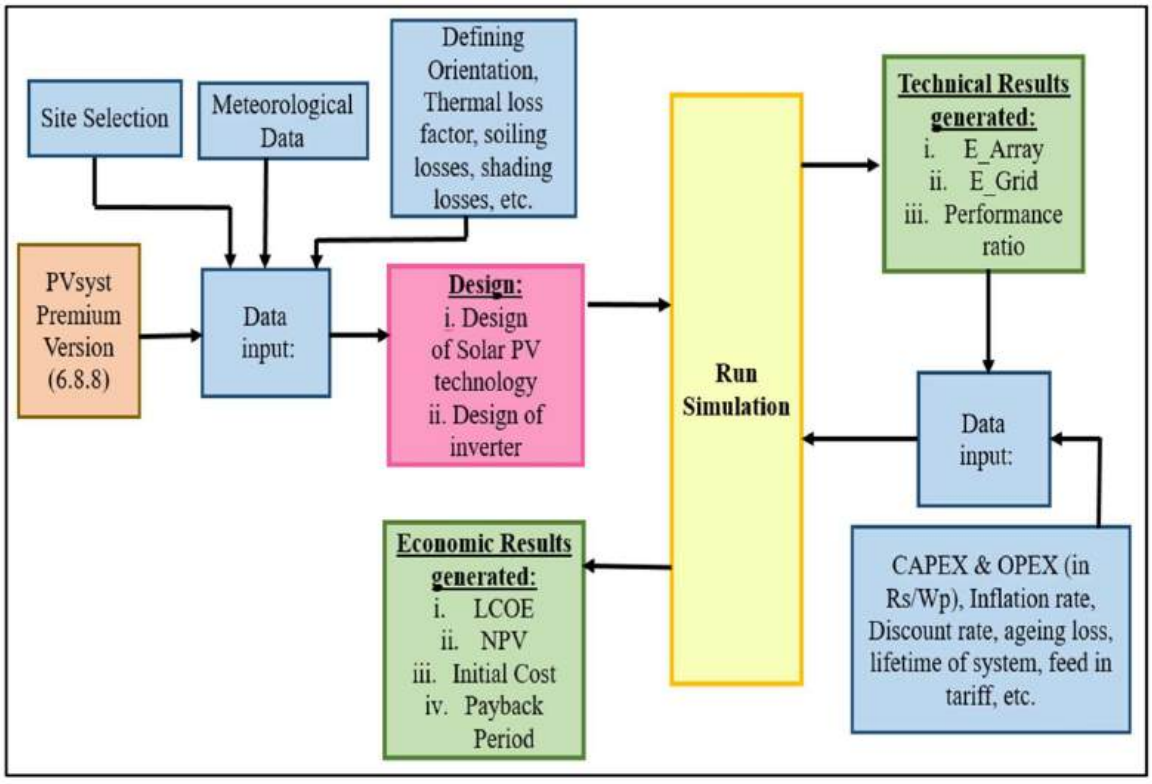

Fig 2.3: Methodology block diagram for PVsyst software

2.2.3 Data inputs given for designing in PVsyst:

A. Meteorological data

Meteorological data for research have been collected using the metronome 7.2 data source and PVsyst software. The annual levels of irradiation vary from 122.1 to 205.3 kWh/m^2. Using MATLAB code, monthly solar irradiance is evaluated using ambient temperature and wind velocity from PVsyst software (version 6.8.8). Table 2.1 shows solar irradiation data of Ambazari Lake.

Table 2.1: Solar Irradiation Data of Ambazari Lake

Month	Horizontal Global irradiation (kWh/m^2)	Horizontal diffuse irradiation (kWh/m^2)	Temperature (°C)	Wind Velocity (m/s)
Jan	138.1	45.42	20.96	0.7
Feb	148.0	47.38	23.80	0.99
Mar	187.8	62.39	28.16	1.19
Apr	196.6	69.42	31.58	1.40
May	205.3	79.41	34.77	1.81
Jun	156.1	98.87	30.57	2.08
Jul	123.9	85.72	27.62	2.10
Aug	122.1	92.85	26.86	1.79
Sep	143.3	67.97	27.09	1.19
Oct	156.2	55.52	26.32	0.70
Nov	136.2	48.56	22.90	0.59
Dec	132.2	43.10	20.63	0.49
Year	**1845.8**	**796.7**	**26.78**	**1.3**

B. FSPV system layout

The configuration of PV modules in series and parallel can be determined using the formulas provided below. The total number of PV modules is calculated by dividing the total capacity of the PV plant by the rated power of an individual module. The number of panels in a single string is derived by dividing the inverter's voltage rating by the maximum voltage of a solar module. Subsequently, the number of strings is obtained by dividing the total number of PV modules by the number of modules per string.

$$\textbf{Total No. of PV modules} = \frac{\textbf{Total PV plant capacity}}{\textbf{Rated power of PV module}} \quad (2.1)$$

$$= \frac{5*1000\,W}{250\,W} = \mathbf{20}$$

$$\textbf{No. of PV module in String} = \frac{\textbf{Max. Voltage of inverter}}{\textbf{Max. voltage of solar module}} \quad (2.2)$$

$$= \frac{300}{28.9} = \mathbf{10.3 \sim 10}$$

$$\textbf{No. of strings in parallel} = \frac{\textbf{Total no. of PV modules}}{\textbf{No. of PV modules in string}} \quad (2.3)$$

$$= \frac{20}{10} = \mathbf{2}$$

Calculations showed that the FSPV system consists of 20 PV modules, one inverter, and one battery energy storage system. It has two strings, each consisting of 10 modules in series. Table 2.2 shows the specifications of the PV modules and Inverters.

Table 2.2: PV Module and Inverter Specification

Manufacturer	**Generic**
PV module model	Poly 250Wp 60 cells
DC Power rating	4.8 kW
AC Power rating	4.2 kW
PV module rating	250 W
Total no. of PV modules	20
No. of modules in string	10
No. of strings	2
Inverter model	4.2 kW
No. of inverters	1

2.3. Technical Performance Analysis

The primary factors affecting the variation in performance indicators between FSPV and GSPV systems are the cell operating temperature and the resulting thermal and environmental losses.

A. Solar Irradiation on tilted PV plane:

$$H_o = \left(\frac{24}{\pi}\right) * L * (cos\delta * cos\varphi * sinw_{sr} + sin\delta * sin\varphi * w_{sr}) \quad (2.4)$$

$$H_{at} = \left[\left(1 - \gamma_T * \left(\frac{1+cos\beta}{2}\right) + \rho\left(\frac{1-cos\beta}{2}\right)\right] * K_T * H_O \quad (2.5)$$

Where, δ = declination angle (degree), L = solar insolation (kW/m^2), β = tilt angle (radians), φ = latitude angle (radians), γ_T = overall tilt factor, w_{sr} = sunrise angle (radians), R_d = the tilt factor, ρ = reflection coefficient, K_T = clearness index, H_o = solar irradiation incident on horizontal PV module (kW/m^2/day).

B. Module Temperature:

$$T_{mod} = \frac{(T\alpha - \eta) * G}{U} + T_{amb} \quad (2.6)$$

$$U = U_C + (U_V * V) \quad (2.7)$$

Where T_{amb} = Ambient temperature (°C), G = Solar irradiance (W/m^2), and $T\alpha$ = transmittance and absorptance product, U = total heat loss coefficient (W/m^{2}K), U_v = wind dependent heat loss coefficient (W/m^{2}K/m/s), U_c = heat loss coefficient, V = wind speed (m/s).

C. Performance Ratio:

It is defined as the ratio of the actual AC power output to the theoretical energy output if all incident solar energy under Standard Test Conditions (STC) were fully converted into electrical energy. A well-designed PV plant typically achieves a performance ratio of around 80%.

$$PR = \frac{Final\ yield}{Reference\ yield}\ or\ PR = \frac{E_{FSPV}}{G*A*\eta} \quad (2.8)$$

Where E_{FPV} = the total energy yield from the modules (kWh), A = total module area (m^2), η = the efficiency of the module in percentage and G = incident solar radiation (kWh/m^2).

D. Capacity Utilization Factor:

The Capacity Utilization Factor (CUF) represents the ratio between the actual energy generated by the photovoltaic system over a year and the energy it could have produced if it operated at its full rated capacity under ideal conditions throughout the same period.

$$CUF = \frac{Actual\ output}{Plant\ capacity * 8760} \quad (2.9)$$

E. Normalized Performance Indexes:

i. $$Reference\ yield\ (Yr) = \frac{H_{at}}{G \times d} \quad (2.10)$$

ii. $$Array\ yield\ (Ya) = \frac{DC\ Electricity\ produced\ by\ the\ array}{Nominal\ capacity\ of\ the\ plant} \quad (2.11)$$

iii. $$Final\ yield(Yf) = \frac{AC\ Electricity\ suppiled\ to\ the\ grid}{Nominal\ capacity\ of\ the\ plant} \quad (2.12)$$

iv. $$Collection\ loss\ (Lc) = Yr - Ya \quad (2.13)$$

v. $$System\ loss\ (Ls) = Ya - Yf \quad (2.14)$$

F. CO_2 reductions/ savings:

$$Carbon\ saving = Egrid * Project\ lifetime * LCEgrid - LCE\ system \quad (2.15)$$

Where *Egrid* = yearly energy yield (kWh/year), *LCE system* = CO_2 emission due to FSPV construction and operation, *LCE (life cycle emission) grid* = CO_2 emissions associated with generating one unit of electricity from the power grid.

2.4. Economic Analysis

2.4.1 Cost estimation of FSPV plant

Table 2.3 represents the breakdown of the total cost involved in the proposed 5kWp FSPV plant. The total cost involved is Rs.306400 for the proposed 5kWp FSPV system

Table 2.3: Cost Estimation of the proposed 5kWp FSPV plant

Sr. No.	Item	Quantity (in units)	Cost (INR)	Total Cost (INR)
1.	PV Modules: (Poly 250 Wp 60 Cells)	20	5247.50	104950
2.	Support for Module	20	3147.50	62950
3.	Inverter	1	25200	25200
4.	Other Components (Accessories, design, construction, testing, and commission)			113300
	Total			**306400**

2.4.2 Assumptions are used to calculate the cost of electricity

The Following Assumptions given in Table 2.4, are taken into consideration for the calculation of cost of electricity,

Table 2.4: Parameters considered for economic analysis

Sr. No.	Parameter	GSPV	FSPV
1.	Total capital cost of the plant (in Rs.)	2.603 lakh	3.064 lakh
2.	Yearly O&M Cost (in Rs.)	4550	6447.62
3.	Life of the system (in years)	25	25
4.	Opex inflation rate (in % per year)	3	3
5.	Debt : Equity ratio	70:30	70:30
6.	Equity component (in Rs.)	1.82 lakh	2.14 lakh
7.	Debt component (in Rs.)	78090	91920
8.	Tenure of loan (in years)	15	15
9.	Annual energy production (kWh)	7.651	8.168
10.	Discount rate (in % per year)	10	10
11.	Yearly decrement in the generation (in %)	1	1

2.4.3 Calculations for economic analysis

Following performance indices are considered for economic analysis of proposed FSPV plant.

A. Levelized Cost of Electricity

LCOE accounts for the total investment-related cash flows as well as the revenues from electricity generation, while also considering factors such as system degradation and the applied discount rate.

$$\boldsymbol{LCOE} = \sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t} \Big/ \sum_{t=1}^{n} \frac{E_t}{(1+r)^t} \tag{2.16}$$

Where I_t = Investment expenses (in year t), n = Life of the system (in year), M_t = Operation and maintenance expenses (in year t), r = discount rate, E_t = electricity yield (in year t), and F_t = Fuel expenses (in year t).

B. Return on investment

ROI is calculated as the ratio of a project's net profit to its total investment. A project is considered economically feasible if its ROI exceeds one.

$$\boldsymbol{ROI} = \frac{\textbf{Net profit over the lifetime}}{\textbf{Total investment on project} * 100} \tag{2.17}$$

C. Net Present Value

This term represents the difference between cash inflows and outflows over the operational lifespan of the project. For the project to be considered financially viable, its Net Present Value (NPV) must be positive.

$$\boldsymbol{NPV} = \sum_{t=0}^{N} \frac{P}{(1+i)^t} - \boldsymbol{C} \tag{2.18}$$

Where P = net period cash flow (Rs. / year), i = discount rate (%), t = project lifetime (years), C = initial investment (Rs.).

D. Payback period

It is the duration needed for a project to recoup its initial investment through the earnings it generates. It is determined by dividing the total investment cost of the plant by the yearly savings it produces.

$$\boldsymbol{Payback\ period} = \frac{\boldsymbol{Initial\ investment}}{\boldsymbol{Yearly\ cash\ flow}} \tag{2.19}$$

E. Life Cycle Cost

Life Cycle Cost (LCC) in a solar PV plant is the total cost of owning, operating, and maintaining the system over its entire lifespan, usually 25–30 years.

$$\boldsymbol{LCC = CAPEX} + \sum_{t=1}^{N} \frac{M_t}{(1+r)^t} + \frac{\boldsymbol{Disposal\ cost}}{(1+r)^N} \tag{2.20}$$

Where CAPEX= initial investment, M_t = Operation and maintenance expenses (in year t), r = discount rate in percent, Disposal cost = cost incurred at the end of the system life, N = Life of the system (in years).

2.5. Simulation Results and Discussions

The technical performance of the 5 kWp FSPV system was analyzed using PVsyst software. This analysis included monthly global effective radiation, energy output from the panels, and the electricity fed into the grid. An inverter efficiency of 98% was taken into account. The system recorded an annual average solar radiation of 1845.8 kWh/m², with a total energy yield of 8.460 MWh from array and 8.168 MWh is delivered to the grid. A performance ratio of 0.823 was achieved, indicating superior efficiency compared to GSPV systems. The CUF was found to be 18.64%. A detailed overview of monthly average technical parameters is presented in Table 2.5.

Table 2.5: Technical parameters of FSPV plant

Month	E_array (MWh)	PR	T_mod (in °C)
Jan	0.766	0.844	43.10
Feb	0.760	0.832	45.94
Mar	0.859	0.812	50.30
Apr	0.807	0.798	53.72
May	0.785	0.793	56.91
Jun	0.613	0.822	52.71
Jul	0.503	0.836	49.76
Aug	0.509	0.837	49.00
Sep	0.633	0.823	49.23
Oct	0.750	0.819	48.46
Nov	0.725	0.835	45.04
Dec	0.747	0.842	42.77
Yearly	**8.460**	**0.823**	**48.91**

2.5.1. Energy generated from the FSPV and GSPV system

The presence of water beneath floating PV modules provides a natural cooling effect, which helps lower the PV cell temperature and consequently reduces energy losses. Various types of losses, including soiling, wiring, shading, connection, light-induced degradation, mismatch, nameplate rating, and availability, are taken into account using the PVWatts calculator. Floating Solar PV (FSPV) systems experience lower soiling losses compared to Ground-Mounted Solar PV (GSPV) systems; for simulation purposes, soiling losses are assumed to be 3% for GSPV and 2% for FSPV. The overall system losses are calculated to be 14.08% for GSPV and 12.30% for FSPV. When compared to GSPV systems, FSPV systems show an annual energy gain of 2.50% based on PVWatts results and a 6.67% higher energy output according to PVsyst simulations.

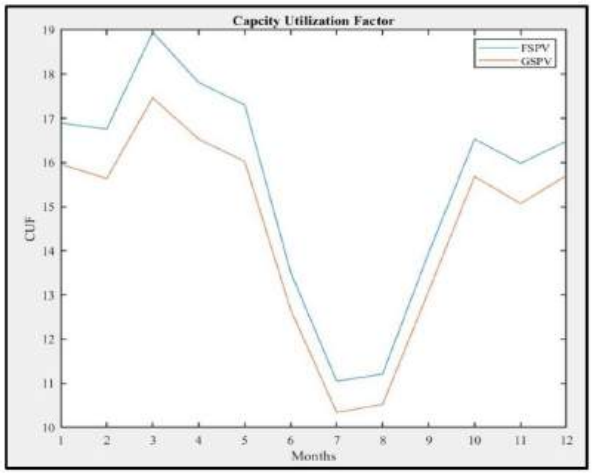

Fig. 2.4: Annual capacity utilization factor of GSPV and FSPV system

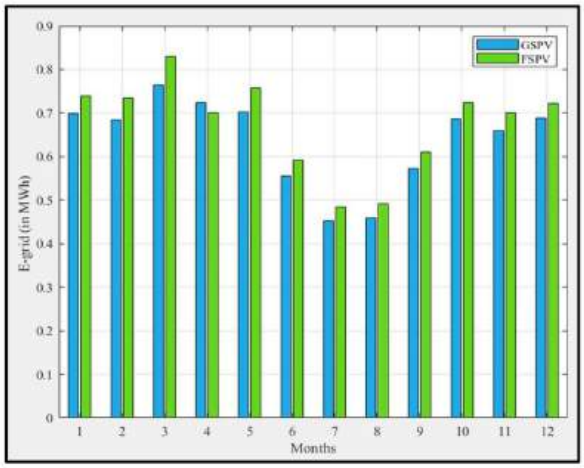

Fig. 2.5: Annual energy yield injected into the grid from GSPV and FSPV system

Fig. 2.4 shows the monthly CUF of GSPV and FSPV. Fig.2.5 shows the energy generation injected into the grid from GSPV and FSPV plant.

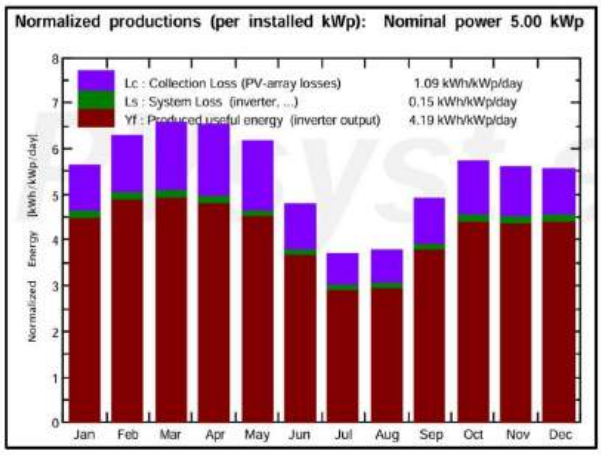
Normalized productions (per installed kWp): Nominal power 5.00 kWp
Lc : Collection Loss (PV-array losses) 1.09 kWh/kWp/day
Ls : System Loss (inverter, ...) 0.15 kWh/kWp/day
Yf : Produced useful energy (inverter output) 4.19 kWh/kWp/day
Normalized Energy [kWh/kWp/day]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Fig. 2.6: Normalized Performance Index of 5kWp GSPV plant.

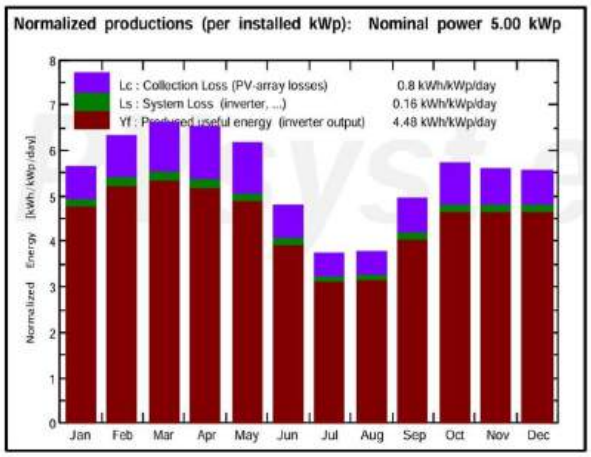
Normalized productions (per installed kWp): Nominal power 5.00 kWp
Lc : Collection Loss (PV-array losses) 0.8 kWh/kWp/day
Ls : System Loss (inverter, ...) 0.16 kWh/kWp/day
Yf : Produced useful energy (inverter output) 4.48 kWh/kWp/day
Normalized Energy [kWh/kWp/day]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Fig. 2.7: Normalized Performance Index of proposed 5kWp FSPV plant.

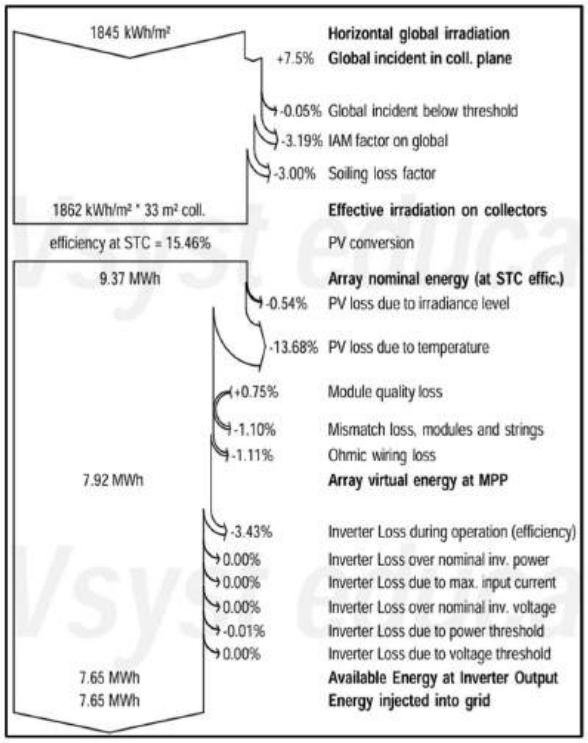

Fig. 2.8: Sankey Diagram for 5kWp GSPV system

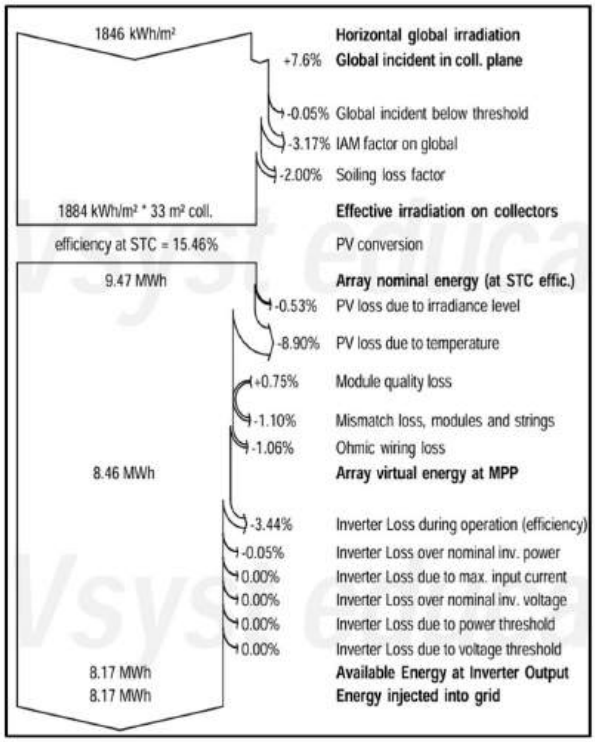

Fig. 2.9: Sankey Diagram for proposed 5kWp FSPV system

PVsyst software simulation provides array energy output and detailed loss analysis. It includes the produced useful energy, system losses, and collection system losses. Collection losses represent losses associated with the PV modules themselves, while system losses include components such as inverter losses and other system-related inefficiencies. Fig.2.6 and 2.7 show the normalized performance index of GSPV and FSPV, respectively.Fig.2.8 and 2.9 show the Sankey diagram (which shows the flow of energy from the plant to the grid) for the GSPV and proposed FSPV plant, respectively.

Table 2.6 compares the energy yield from GSPV and FSPV plants, which is obtained from the PVsyst software and PVwatt calculator. Table 2.7 compares technical parameters of GSPV and FSPV plants.

Table 2.6: Comparison of energy yield from PVsyst software and PVWatt calculator.

Mounting Type	PVWatt Calculator	PVsyst Software
GSPV	7598	7651
FSPV	8095	8168

Table 2.7: Technical parameters of GSPV and FSPV plant.

Parameter	GSPV	FSPV
Module temperature (°C)	63.245	48.9178
Annual energy yield (MWh)	7.651	8.168
PR (in %)	77.2	82.3
CUF (in %)	17.4658	18.6438
Power loss due to temperature	-13.68	-8.90
Yf (kWh/kWp/day)	4.19	4.48
Lc (kWh/kWp/day)	1.09	0.8
Ls (kWh/kWp/day)	0.15	0.16
CO_2 emission /savings (tCO_2/year)	176.6	189.2

2.5.2. Economic Analysis Results of the FSPV Plant

The total installation cost for the proposed 5 kWp FSPV plant is Rs.306400. With a project lifespan of 25 years, an inflation rate of 3%, and a discount rate of 9.46%, the LCOE, calculated using PVsyst simulations with straight-line depreciation over 15 years, is Rs.3.080/kWh. The recovery period (payback period) of the project's upfront investment for the project is estimated at 10.6 years, indicating that the initial investment will be recovered within this timeframe. The Net Present Value (NPV) of the project is Rs.385419.43. Economic analysis parameters are presented in Table 2.8.

Table 2.8: Economic parameters of proposed FSPV plant

Parameter	GSPV	FSPV
Total Installation Cost	Rs.260300	Rs.306400
Levelized Cost of Electricity (LCOE)	3.383 Rs / kWh	3.080 Rs / kWh
Payback period	11 years	10.6 years
Net Present Value (NPV)	Rs. 300095.26	Rs. 385419.43
Return on Investment (ROI)	115.3%	125.8%

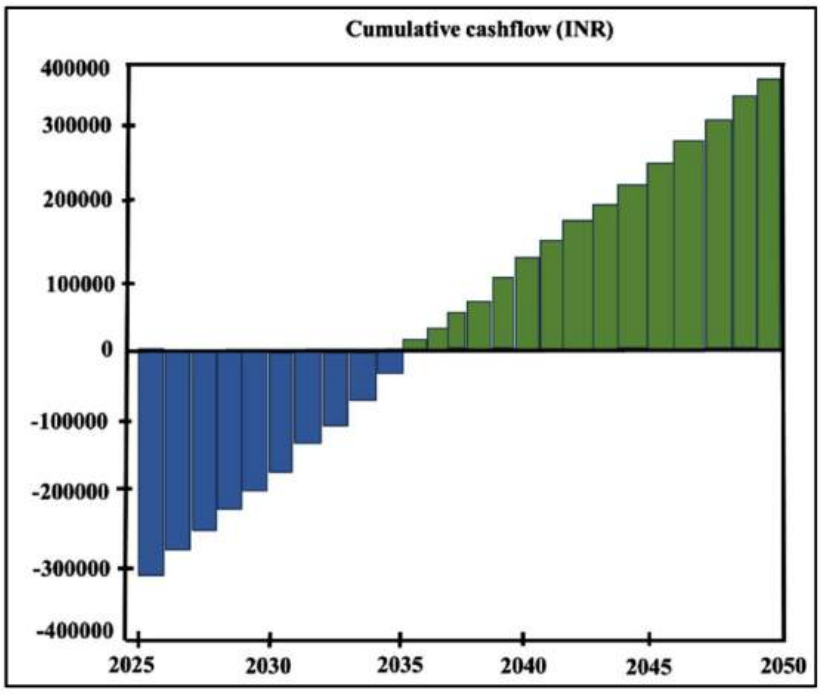

Fig. 2.10: Cumulative cashflow of FSPV system.

2.5.3. Comparison of FSPV and GSPV plant results

Table 2.9 show the technical and economic parameters of the proposed 5kWp GSPV and FSPV plant at Ambazari Lake, Nagpur, Maharashtra.

Table 2.9: Comparison of results of GSPV plant and FSPV plant.

Parameter	GSPV	FSPV
Module temperature (°C)	63.245	48.9178
Annual energy yield (MWh)	7.651	8.168
PR (in %)	77.2	82.3
CUF (in %)	17.4658	18.6438
Power loss due to temperature	-13.68	-8.90
Yf (kWh/kWp/day)	4.19	4.48
Lc (kWh/kWp/day)	1.09	0.8
Ls (kWh/kWp/day)	0.15	0.16
CO_2 emission /savings (tCO_2/year)	176.6	189.2
Total Installation Cost (in Rs.)	260300	306400
Levelized Cost of Electricity (LCOE) (in Rs. / kWh)	3.383	3.080
Payback period (in years)	11	10.6
Net Present Value (NPV) (in Rs.)	300095.26	385419.43
Return on Investment (ROI) (in %)	115.3	125.8
Life Cycle Cost (LCC) (in Rs.)	347901.35	366284.20

2.6. Conclusion

This chapter presents the design and techno-economic assessment of the proposed 5 kWp FSPV system. The system is projected to produce approx. 8.168 MWh of electricity annually, achieving a PR of 82.3% and a CUF of 18.6483%. Simulation results indicate that the FSPV setup delivers a 2.50% higher energy output compared to GSPV systems based on PVWatts, and a 6.67% improvement according to PVsyst simulations. The economic evaluation estimates the LCOE for the 5 kWp FSPV plant to be Rs.3.080/kWh, with a total estimated investment of Rs.3,06,400. The time required to recover this investment, is calculated to be approximately 10.6 years. Overall, the FSPV system offers improved economic and environmental performance over GSPV systems, with benefits such as increased energy output, reduced LCOE, higher return on investment, and better carbon savings, despite a marginally higher life cycle cost.

CHAPTER 3: TECHNO-ECONOMIC ANALYSIS OF THE PROPOSED 5kWp TRACKING TYPE FSPV PLANT.

3.1. Introduction

To maximize energy absorption, the angle of incidence is the angle between incoming sunlight and the surface of a solar collector, should be minimized. Tracking systems, which adjust the position of solar panels throughout the day to follow the sun's path, help achieve this goal. These systems optimize exposure to solar radiation, extending the duration of energy capture and improving overall energy output compared to fixed mount installations. On a clear day, a photovoltaic (PV) module receives solar radiation from three main components: diffuse, beam, and reflected radiation. Among these, beam radiation is the most significant, while diffuse and reflected radiation make smaller contributions [2]. The total solar radiation under clear-sky conditions can be represented as follows:

$$I_c = I_{rc} + I_{dc} + I_{bc} \tag{3.1}$$

$$I_c = A * e^{-km} * [cos\beta * cos(\varphi s - \varphi c) * sin\Sigma + sin\beta * cos\Sigma + C\left(\frac{1+cos\Sigma}{2}\right)] \tag{3.2}$$

3.2. Types of Tracking Systems

3.2.1 Single Axis Tracking

In a single-axis tracking (SAT) system, photovoltaic (PV) panels rotate along a fixed axis, aligned either in the North-South or East-West direction, to follow the sun's path. This approach is recognized for its balance of cost-effectiveness and efficiency, making it a preferred option for large-scale, GSPV installations, particularly in areas with direct, intense solar radiation. To achieve optimal energy capture, tilt angle is typically set to match the latitude of the installation site. At the same time, the azimuth angle is continuously adjusted to ensure the PV modules remain oriented toward the sun, which enhances solar energy absorption from morning to evening.

$$\Sigma_{effective} = 90 - \beta + \delta \tag{3.3}$$

Here, δ represents the declination angle, measured in degrees, which varies based on the day of the year. Fig.3.1 represents the single-axis tracking.

3.2.2 Two Axis Tracking

In the two-axis tracking (TAT) system, photovoltaic (PV) panels rotate along both the East-West and North-South axes to precisely follow the sun's trajectory. This alignment ensures that solar radiation strikes the panels perpendicularly throughout the day, maximizing energy absorption and system efficiency. With this tracking technique, the PV module's tilt angle equals the solar zenith angle, and its azimuth angle coincides with the solar azimuth angle. Consequently, the incidence angle remains zero, optimizing the system's performance.

$$\boldsymbol{\Sigma = 90 - \beta} \tag{3.4}$$

The TAT system demonstrates superior performance even on cloudy days compared to single-axis trackers. As a result, it offers higher overall efficiency than single-axis tracking systems. While the two-axis tracker (TAT) is more complex, it offers greater efficiency and cost-effectiveness when compared with fixed tilted and single-axis trackers. Fig.3.2 represents the two-axis tracking.

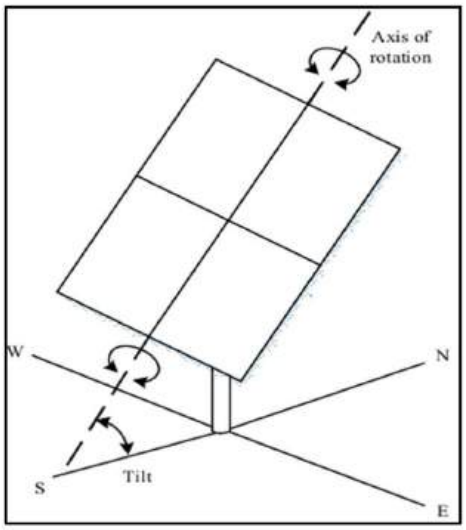

Fig. 3.1: Single-axis tracking (rotating along the North-South axis) [2]

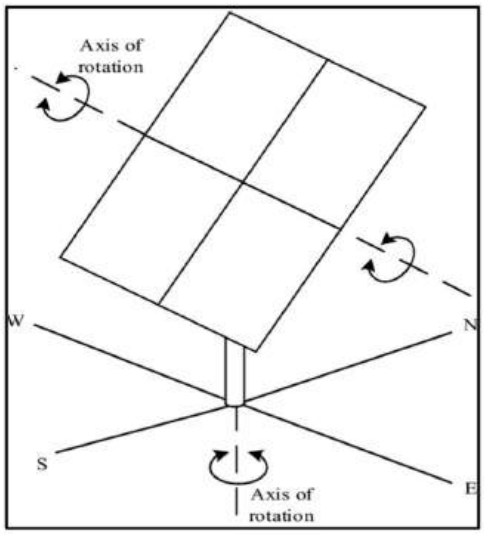

Fig. 3.2: Two axis tracking [2]

3.3. Benefits and Challenges of Tracking Systems in the FSPV plant.

3.3.1 Benefits of a Tracking System

- Tracking systems in floating solar installations enhance power output by continuously adjusting the panels are oriented to follow the sun's path during the day. This dynamic positioning ensures that solar radiation hits the panels at the most effective angle, increasing the total energy produced compared to fixed-angle panels [2].
- Because floating solar panels rest on water surfaces, the cooling effect of the water helps maintain lower panel temperatures. Cooler panels operate more efficiently, and when combined with tracking systems, this cooling can further boost energy generation.
- By optimizing the angle of incidence, tracking systems maximize the use of limited water surface area, producing more electricity from the same footprint. This is particularly valuable in regions where water bodies are the only available spaces for solar installations.
- The shading effect of floating solar panels reduces water evaporation from reservoirs, which benefits water conservation efforts. When tracking systems tilt panels optimally, this shading can be enhanced, helping preserve precious water resources.
- Additionally, tracking systems often extend the hours during which solar panels can effectively capture sunlight, increasing overall generation time each day. This longer exposure to direct sunlight contributes to a better return on investment over the system's lifetime.
- Floating solar with tracking also supports more predictable and stable energy production patterns, which facilitates integration with smart grids and improves energy management strategies.

3.3.2 Challenges of the Tracking system

- Incorporating tracking mechanisms into floating solar systems adds mechanical complexity. Moving parts are subject to wear and tear, especially in aquatic environments where moisture and corrosion are concerns, which may lead to increased maintenance demands.

- The initial costs of installing tracking systems are higher than those of fixed solar arrays. This includes expenses related to the tracker hardware, more robust floating platforms to support moving components, and advanced control systems.
- Floating platforms face continuous movement due to waves, wind, and water currents. This instability can cause misalignment or stress on tracking components, potentially reducing their lifespan or requiring more frequent adjustments.
- Maintaining tracking systems on water is more challenging than on land. Accessing the equipment for repairs or cleaning requires specialized procedures and may incur higher operational costs.
- Furthermore, tracking systems consume a portion of the energy they generate to power motors and sensors that enable movement. Although this energy use is relatively small, it slightly reduces the net energy output.

3.4. Techno-economic analysis of tracking-type FSPV system.

Meteorological data have been collected using the Metronome 7.2 data source and PVsyst (version 6.8.8). Using MATLAB code, monthly solar irradiance is evaluated by using ambient temperature and wind velocity from PVsyst software (version 6.8.8). From Table 2.1. Solar irradiation data for Ambazari Lake is taken. Fig.3.3 shows the comparison between monthly average irradiation for fixed tilted plane, single-axis, and two-axis tracking systems. Fig. 3.4 compares temperatures of floating and ground-mounted PV modules. The result shows that FSPV has lower temperatures than GSPV.

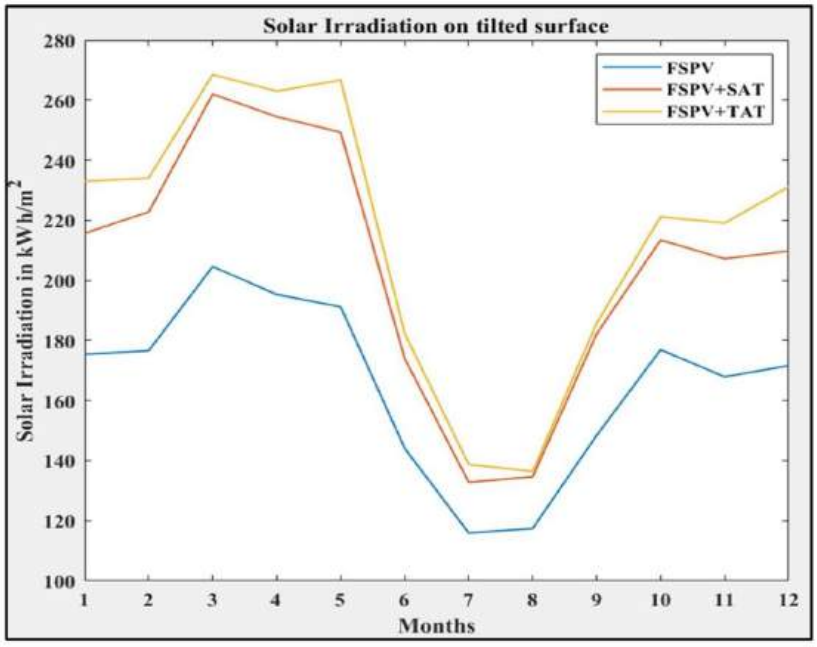

Fig. 3.3: Monthly average solar irradiation (in kWh/m^2) on Ambazari Lake

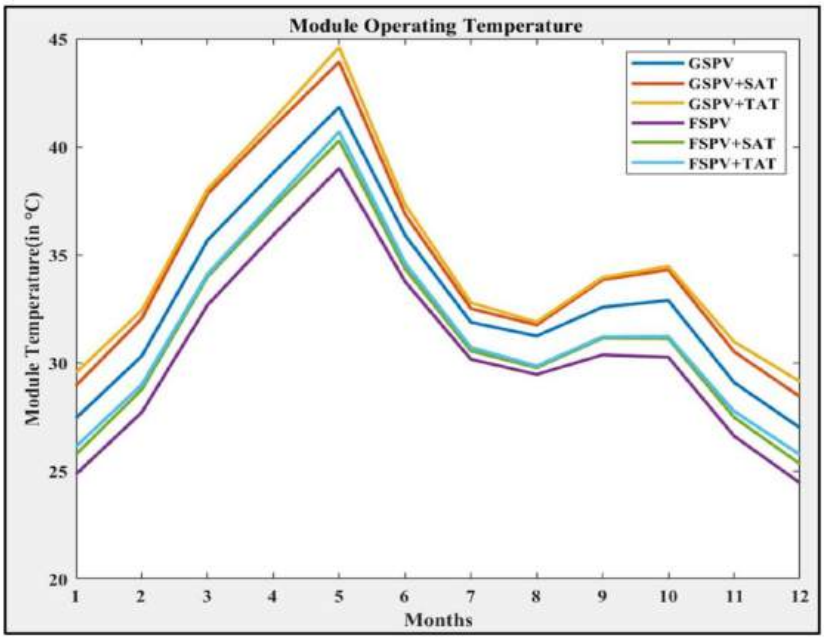

Fig. 3.4: Operating temperature of the module at Nagpur

3.5. Simulation Results and Discussions

3.5.1 Technical parameters and performance of the FSPV plant

Fig. 3.5 shows the monthly energy generated by the 5kWp fixed tilted plane, single-axis tracking, and two-axis tracking FSPV system. Fig. 3.6 shows the annual energy generated by the 5kWp fixed tilted plane, single-axis tracking, and two-axis tracking FSPV and GSPV systems.

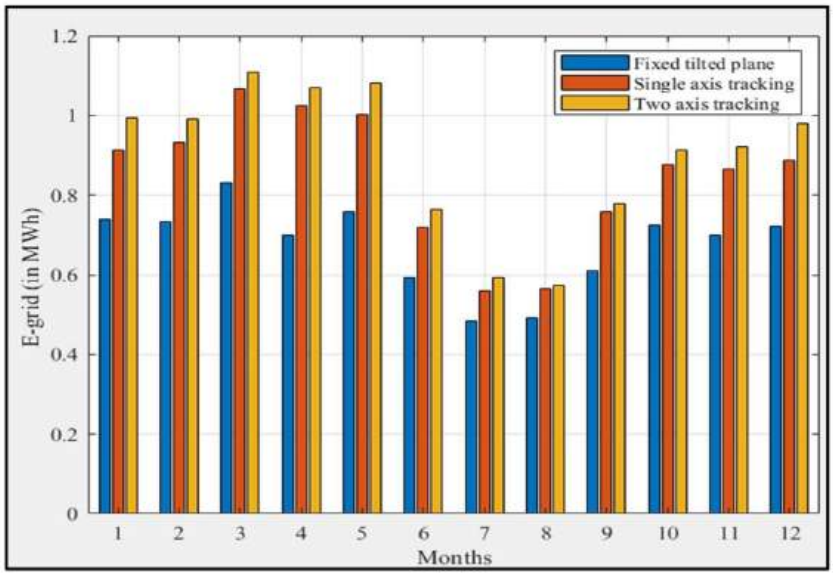

Fig. 3.5: Energy yield for 5kWp fixed and tracking type FSPV plant

Table 3.1 shows the comparative analysis between the fixed tilted, single, and two-axis tracking FSPV system obtained from PVsyst software and MATLAB. The annual energy yield increases with tracking systems due to improved solar exposure, as SAT generates 24.4% more energy than the fixed tilted plane, while TAT produces 31.1% more. The PR (as shown in Fig. 3.7) is slightly higher in tracking systems because of optimized sunlight absorption, with SAT improving by 0.6% and TAT by 0.97%. In contrast, GSPV systems also show similar characteristics, i.e., a slight increase in PR, tracking 77.2% for fixed, 77.9% for single-axis, and 78.5% for two-axis. The CUF (as shown in Fig. 3.8) for SAT showed a 23.21% increase, and TAT demonstrated a 24.57% improvement. For the GSPV system, the CUF for the fixed, single-axis, and two-axis configurations is 17.47%, 21.64%, and 22.57%, respectively. This is because tracking mechanisms help maintain optimal panel orientation, allowing for better energy conversion. However, PV losses due to temperature are higher in

tracking systems since prolonged sun exposure increases panel heating. SAT experiences 9.3% more loss, while TAT faces a 14.4% increase compared to the fixed tilted plane. Temperature-related PV losses in GSPV also increase with tracking, reaching -15.18% in the single-axis system and -15.77% in the two-axis system. Despite this, the final yield improves, with SAT delivering 24.3% more output and TAT providing 31% more due to better energy capture throughout the day.

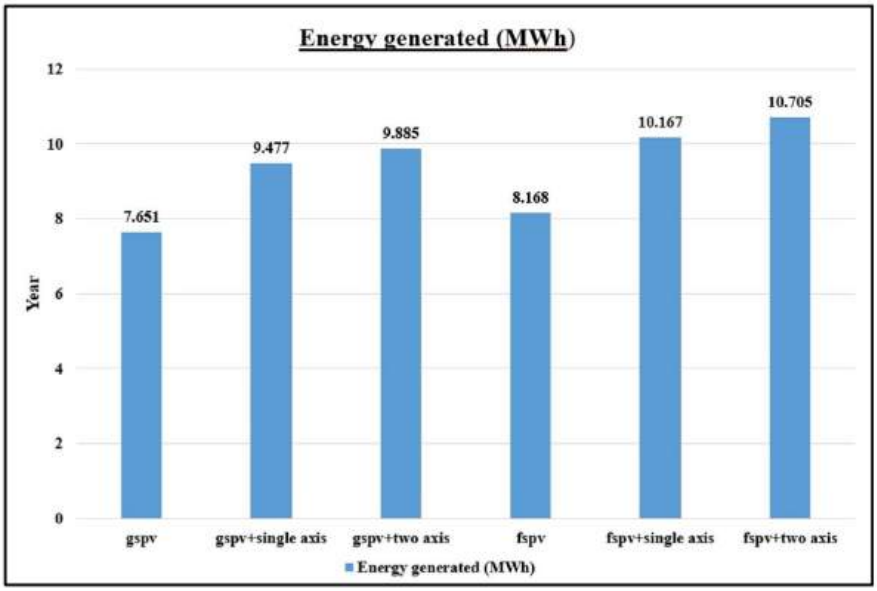

Fig. 3.6: Annual energy yield for a 5kWp proposed fixed and tracking type FSPV & GSPV system

Losses also increase with tracking systems, primarily due to additional mechanical components and energy consumption for movement. Collection losses are 21.3% higher in SAT and 28.8% higher in TAT compared to the fixed tilted plane. System losses follow a similar pattern, with SAT showing an 18.75% increase and TAT experiencing a 6.25% rise. These losses occur because of increased energy usage for panel movement and additional system inefficiencies. However, the environmental benefits are notable, as CO_2 emission savings improve with tracking. Emission reductions improve with tracking, SAT cuts CO_2 by 23% more, and TAT by 30% more, relative to fixed systems. This is a result of higher energy generation, reducing dependency on conventional power sources. While tracking systems significantly enhance energy output and sustainability, they also introduce additional losses

and operational complexities. CO_2 emission savings in GSPV systems also show improvement, with 182.3 tCO_2/year for SAT and 226 tCO_2/year for TAT. TAT provides the highest energy yield and emission savings, but at the cost of increased losses.

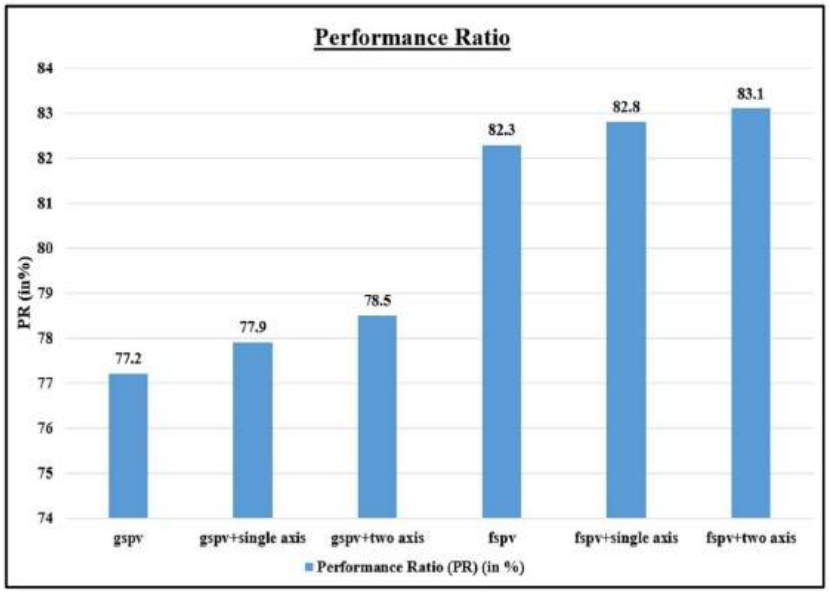

Fig. 3.7: Annual Performance Ratio for 5kWp proposed fixed and tracking type FSPV & GSPV system.

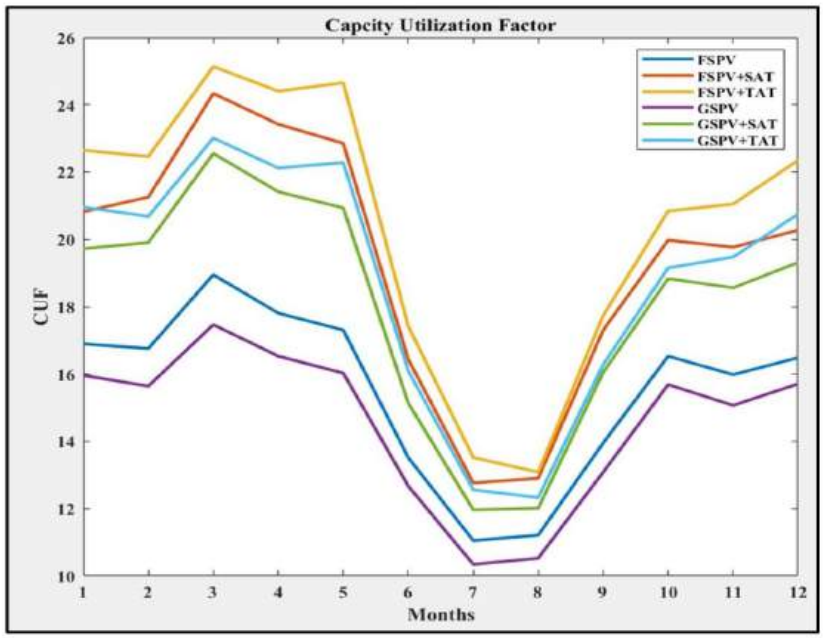

Fig. 3.8: Capital Utilization Factor for 5kWp proposed fixed and tracking type FSPV & GSPV system.

Table 3.1: Comparative analysis of Technical Parameters for FSPV system.

Sr. No.	Parameter	Fixed tilted plane	Single Axis Tracking	Two Axis Tracking
1.	Module temperature (°C)	30.43	31.30	31.53
2.	Annual energy yield (MWh)	8.168	10.167	10.705
3.	PR (in %)	82.3	82.8	83.1
4.	CUF (in %)	18.64	23.21	24.57
5.	PV loss due to temperature	-8.90	-9.73	-10.18
6.	Final yield (kWh/kWp/day)	4.48	5.57	5.87
7.	Collection loss (kWh/kWp/day)	0.80	0.97	1.03
8.	System loss (kWh/kWp/day)	0.16	0.19	0.17
9.	CO_2 emission /savings (tCO_2/year)	189.2	232.7	246

3.5.2 Economic parameters and performance of the FSPV plant

Table 3.2. shows the financial comparison of different solar panel configurations, including fixed tilted plane, SAT, and TAT. The total installation cost is highest for TAT at ₹393,450, which is 28.4% more than the fixed tilted plane, while SAT costs ₹366,400, making it 19.6% more expensive than the fixed system. This is due to the additional mechanical components required for tracking systems. The Levelized Cost of Energy (LCOE) remains almost the same for the fixed and SAT systems at ₹3.080/kWh and ₹3.008/kWh, respectively, but is lower for TAT at ₹2.928/kWh, indicating better cost efficiency over its lifetime. The payback period is slightly shorter for tracking systems, with SAT requiring 10.4 years and TAT taking 10.3 years, compared to 10.6 years for the fixed tilted plane. This suggests that tracking systems generate more revenue in the long run, leading to faster returns.

Table 3.2: Comparative analysis of Economic Parameters for FSPV system.

Sr. No.	Parameter	Fixed Tilted Plane	Single Axis Tracking	Two Axis Tracking
1.	Total Installation Cost (in Rs.)	306400	366400	393450
2.	LCOE (in Rs /kWh)	3.080	3.008	2.928
3.	Payback period (in years)	10.6	10.4	10.3
4.	NPV (in Rs.)	385419.43	476327.48	540930.99
5.	ROI (in %)	125.8	130.0	137.5
6.	LCC (in Rs.)	366284.20	448080.50	506613.10

The Net Present Value (NPV) is highest for TAT at ₹540,930.99, which is 40.5% more than the fixed tilted plane and 13.5% more than SAT, indicating better profitability. SAT also performs well, with an NPV of ₹476,327.48, which is 23.7% higher than the fixed system. The Return on Investment (ROI) follows a similar pattern, with TAT achieving the highest return at 137.5%, followed by SAT at 130%, both outperforming the fixed tilted plane, which has an ROI of 125.8%. The higher ROI in tracking systems is due to increased energy generation, leading to greater financial returns. While tracking systems require a higher initial investment, their better NPV, ROI, and slightly shorter payback period make them financially attractive.

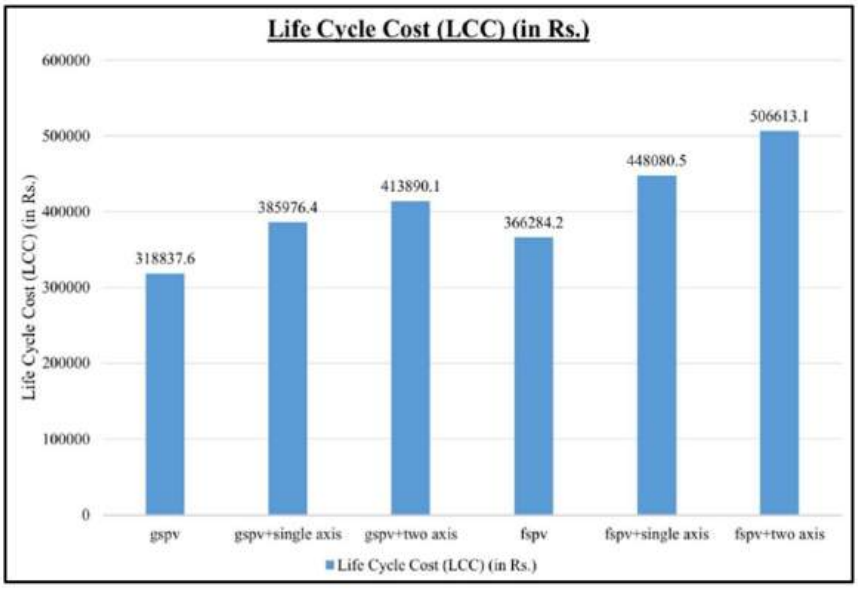

Fig. 3.9: Life Cycle Cost for fixed & tracking type GSPV & FSPV systems

Fig. 3.9 shows that FSPV systems have higher LCC than GSPV due to additional costs for floats, anchoring, and waterproofing. Fixed FSPV costs ₹366,284.20, or 14.88% more than fixed GSPV. FSPV with single-axis and two-axis tracking is 16.14% and 22.42% more expensive than their GSPV equivalents, respectively. Although tracking boosts energy yield, it also raises cost and complexity, especially in floating installations.

Fig. 3.10 and Fig. 3.11 show the cumulative cashflow of SAT and TAT, respectively of FSPV. Fig.3.12 and Fig. 3.13 show the cumulative cashflow of SAT and TAT, respectively of GSPV, where the negative graph represents the payback period, after which the profit will start to come. The maximum positive value shows the NPV of the system.

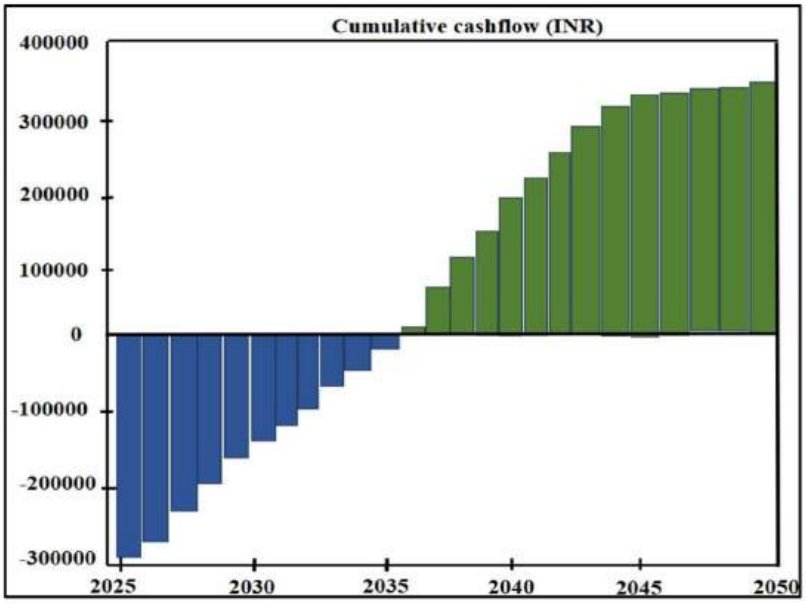

Fig. 3.10: Cumulative cashflow for single-axis tracking GSPV system. (source PVsyst software)

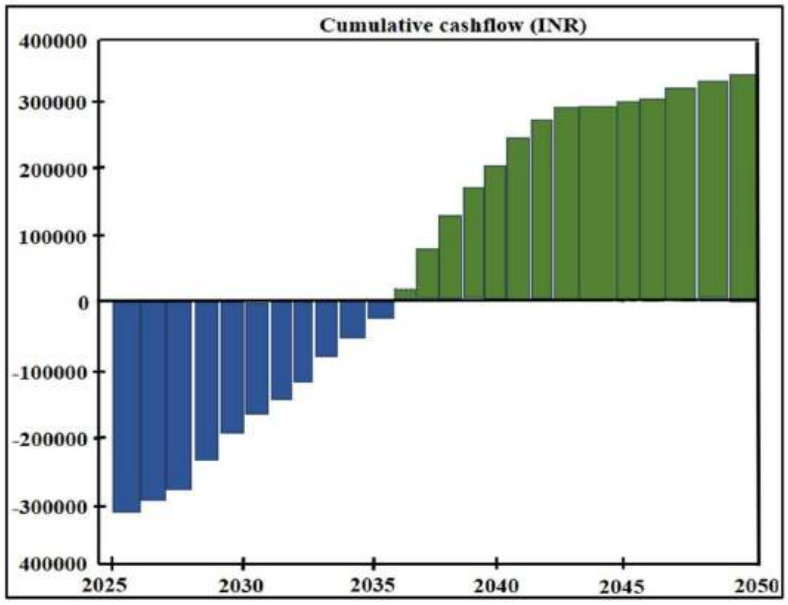

Fig. 3.11: Cumulative cashflow for two-axis tracking GSPV system. (source PVsyst software)

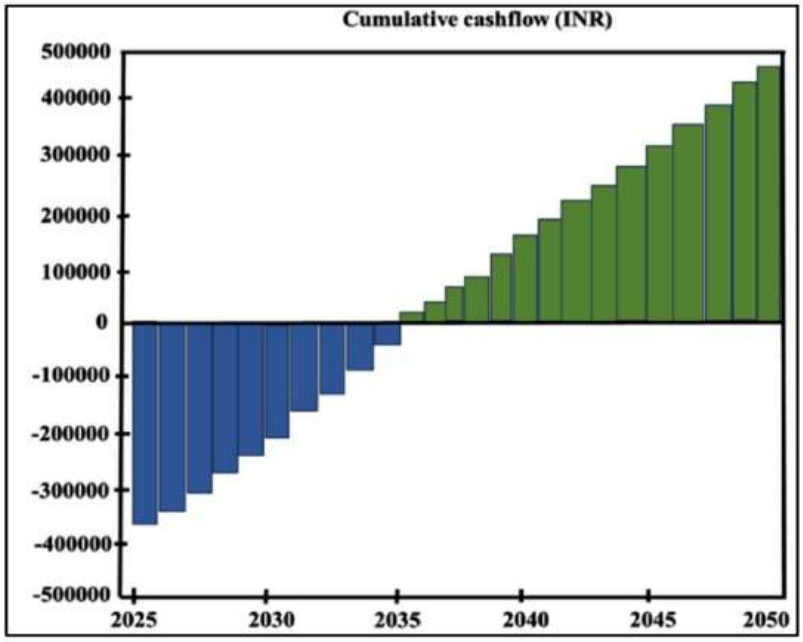

Fig. 3.12: Cumulative cashflow for single axis tracking FSPV system. (source PVsyst software)

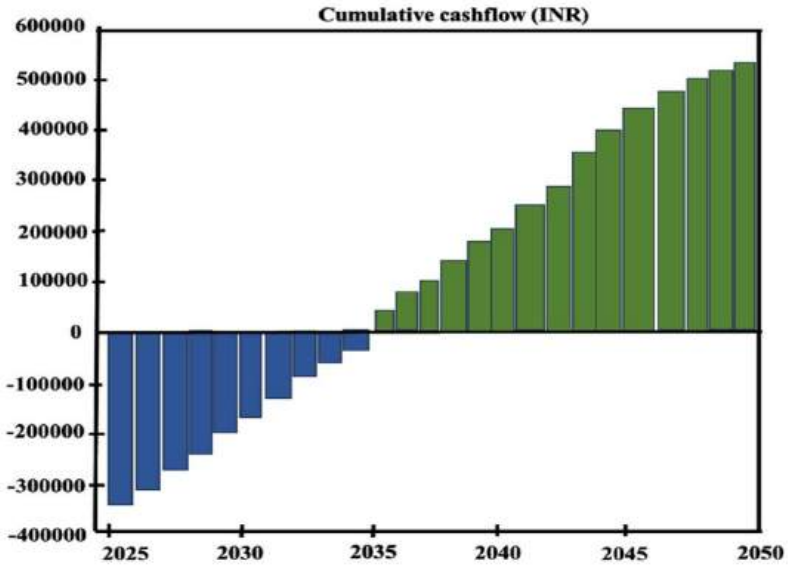

Fig. 3.13: Cumulative cashflow for two-axis tracking FSPV system. (source PVsyst software)

3.6. Conclusion

The analysis of a proposed 5 kWp floating solar photovoltaic (FSPV) system at Ambazari Lake demonstrates both performance and economic advantages over a fixed tilted plane system. Tracking systems, especially TAT, significantly enhance annual energy yield, CUF, and final yield due to continuous solar alignment, leading to improved energy capture. Although tracking increases PV losses due to prolonged sun exposure and slightly raises system losses, the overall efficiency gain results in greater CO_2 emission savings and environmental benefits. However, the added complexity of mechanical components and additional energy consumption must be considered in system design. Economically, while tracking systems require a higher initial investment and LCC, TAT being the most expensive, they offer lower LCOE, a slightly shorter payback period, and significantly higher NPV and ROI, ensuring better financial returns. TAT yields the highest energy output and profitability but comes with increased losses and operational challenges, whereas SAT provides a balanced approach between energy gain and investment cost. Given the water-based setup at Ambazari Lake, integrating a tracking system can maximize energy production while maintaining economic feasibility, making it a promising option for sustainable power generation.

CHAPTER 4: ANALYSIS OF HYBRID FSPV AND BATTERY ENERGY STORAGE SYSTEM (BESS)

4.1. Introduction

Floating Solar Photovoltaic (FSPV) gained recognition as an effective and promising approach to address land scarcity issues in solar energy deployment. By utilizing water bodies for panel installation, FSPV reduces evaporation and improves solar panel efficiency due to the cooling effect of water. However, the intermittency of solar energy poses challenges for ensuring a reliable power supply. To mitigate this, Battery Energy Storage Systems (BESS) can be integrated with FSPV systems, creating a hybrid setup that enhances energy stability, improves grid integration, and supports load balancing. This section explores the types of BESS and evaluates the potential benefits and limitations of such hybrid systems [4].

4.2. Types of Battery Energy Storage Systems

4.2.1. Lead-Acid Batteries

Lead-acid batteries represent one of the earliest and most prevalent forms of energy storage technology. They function based on a chemical reaction occurring between lead plates and a sulfuric acid electrolyte. These batteries are relatively inexpensive and have a simple design, making them a common choice for off-grid and backup power applications. However, they have several drawbacks, including a low energy density (meaning they take up more space for the same capacity), shorter lifespan (typically 500–1,000 cycles), and lower efficiency (around 70–80%). Additionally, they need consistent check, including monitoring the electrolyte levels, and are sensitive to deep discharges, which can further reduce their lifespan [26].

4.2.2. Lithium-ion Batteries

Lithium-ion (Li-ion) batteries are a more advanced and efficient energy storage solution compared to lead-acid. They use lithium compounds as the electrode material, offering higher energy density, longer cycle life (2,000–10,000 cycles), and greater efficiency (90–95%). They also require minimal maintenance and can handle deeper discharges without significant

degradation. Their small size and light weight make them well-suited for floating solar systems, especially where space and weight limitations exist.

Lithium-ion batteries outperform lead-acid in almost every aspect. They possess a greater energy density, allowing them to store more energy within a smaller space, crucial for floating solar installations where space is limited. They also have a longer lifespan, reducing replacement costs over time. Additionally, Li-ion batteries charge faster, have higher round-trip efficiency, and require no maintenance, unlike lead-acid batteries, which need periodic checks. While the upfront cost of Li-ion is higher, the total cost of ownership is often lower due to their durability and efficiency [26].

4.3. Benefits and Challenges of a hybrid FSPV system.

4.3.1. Benefits of a hybrid FSPV system with BESS

- **Enhanced Energy Reliability:** A hybrid Floating Solar PV (FSPV) system with Battery Energy Storage (BESS) ensures continuous storage of surplus solar energy generated during peak production periods and delivers it when sunlight is insufficient or unavailable(e.g., at night or during cloudy weather).
- **Grid Stability:** The BESS balances supply and demand, reducing fluctuations and supporting grid stability, especially in areas with intermittent solar generation.
- **Increased Efficiency:** By storing surplus energy, the system minimizes curtailment (wasted solar power) and maximizes utilization.
- **Reduced Transmission Losses:** Floating solar plants are often located near water bodies close to demand centers, and when paired with BESS, they can provide localized power with minimal transmission losses.
- **Environmental Benefits:** Combining FSPV with BESS lowers reliance on fossil fuels, which in turn decreases greenhouse gas emissions and contributes to environmental sustainability and water usage compared to conventional power plants [26].

4.3.2. Challenges of a hybrid FSPV with BESS

1. The integration of BESS (especially lithium-ion) increases the upfront investment, though long-term savings may justify the expense.
2. Over time, batteries lose capacity, requiring eventual replacement, which adds to operational costs.
3. Managing charge/discharge cycles, temperature control (especially for Li-ion), and system integration requires advanced control systems.
4. On floating platforms, the additional weight of batteries must be carefully managed to avoid instability.
5. Improper disposal of batteries (especially lead-acid) can pose environmental risks if not recycled properly [26].

4.4. Techno-economic analysis of FSPV with BESS.

4.4.1. Meteorological data

Meteorological data is given in earlier chapter 2, Table 2.1: solar irradiation data of Ambazari Lake, it is considered same for FSPV with BESS.

4.4.2. FSPV system layout

The FSPV system consists of 20 units of PV modules, one inverter, and one battery energy storage system. In this there are two strings, each string consisting of 10 modules in series. Fig. 4.1 shows the schematic diagram of grid-connected PV system. Table 4.1 shows PV module and Inverter specifications. Table 4.2 shows the Battery specification.

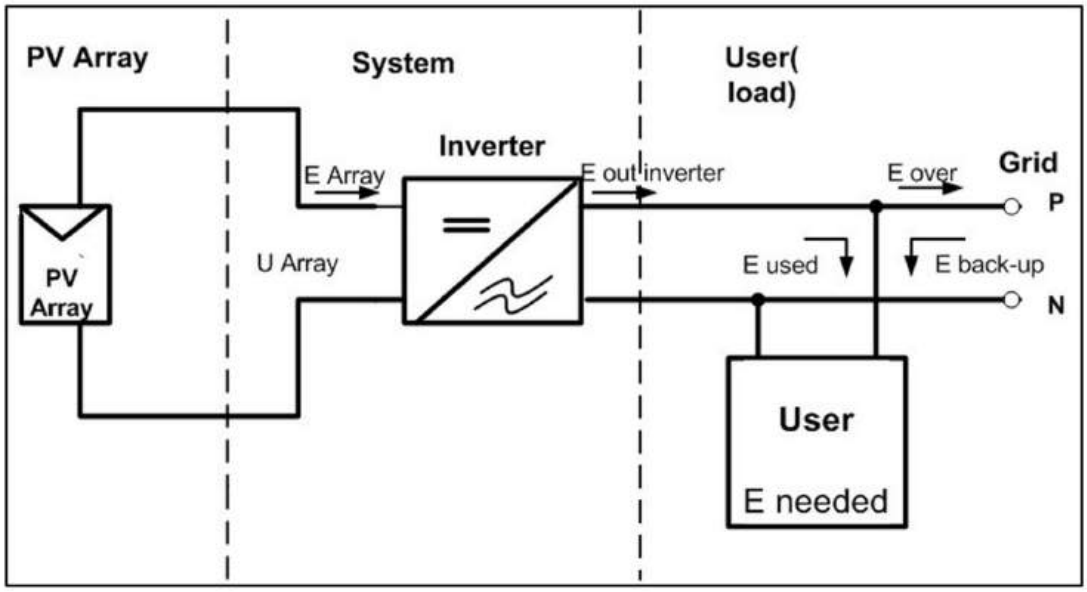

Fig 4.1: Schematic Diagram of Grid connected PV system

Table 4.1: PV Module and Inverter specifications

Manufacturer	Generic
PV module model	Poly 250Wp 60 cells
DC Power rating	4.8 kW
AC Power rating	4.2 kW
PV module rating	250 W
Total no. of PV modules	20
No. of modules in string	10
No. of strings	2
Inverter model	4.2 kW
No. of inverters	1

Table 4.2: Battery specifications

Manufacturer	Generic
Model	Battery module Li-Ion, 26V 180Ah
Max. output power	4.14 kWac
Grid power limit	2.5 kW
Max. charging power	5 kW
Max. discharging power	1.4 kW
Stored energy (80% DOD)	14.7 kWh
Total stored energy during the battery life	28494 kWh

4.4. Simulation Results and Discussions

4.5.1. Technical parameters and performance of the FSPV plant at Ambazari Lake

The energy delivered to the grid and the output generated by the array are determined using PVsyst software. Since cell temperature is the primary difference between the FSPV plant and the GSPV plant, modifications have been implemented to the thermal loss factor. For the FSPV plant, the thermal loss factor (Uc) is set at 24.4 W/m^2K, and for the GSPV plant thermal loss factor (Uc) is set as 20 W/m^2K [30].The 5 kWp FSPV plant array generates 8.460 MWh and an annual energy production of 8.168 MWh. Energy yield in every month of the FSPV plant is shown in Fig. 4.2. Monthly output array energy, performance ratio and module temperature are given in Table 4.3. The PR of the FSPV plant is 0.823, which is more than the 0.772 PR of the GSPV plant. Monthly CUF of GSPV, FSPV and FSPV with BESS are shown in Fig.4.3. Yearly CUF of FSPV is 18.6438% whereas CUF of GSPV is 17.4658%.

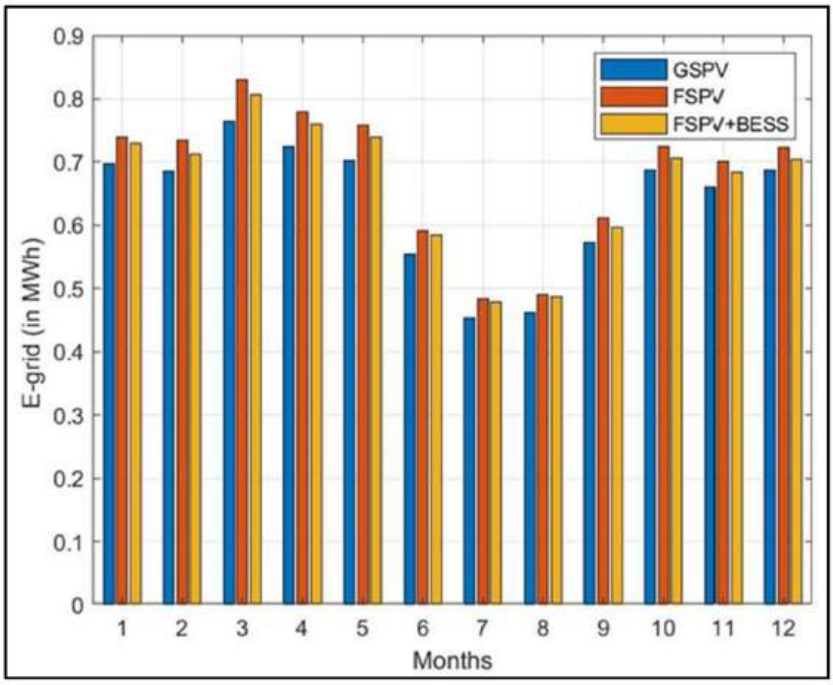

Fig. 4.2: Annual energy yield of GSPV, FSPV and FSPV+BESS.

The FSPV system gains an advantage by operating at cooler temperatures when compared to a GSPV system, which helps improve its overall energy efficiency. This benefit arises mainly from the natural cooling provided by the water beneath the system,

which lowers the operational temperature. As a result of this cooling, the FSPV setup experiences reduced heat-related energy losses. Specifically, the module temperature in the FSPV installation is recorded at 48.91°C, while the GSPV system shows a higher module temperature of 63.24°C. Since module temperature is influenced by surrounding environmental conditions, the lower temperatures in the FSPV setup contribute to higher energy generation than in its ground-mounted counterpart.

Table 4.3. shows the comparative analysis between 5kW GSPV plant, 5kW FSPV plant and 5kW FSPV plant with BESS. FSPV plant has 18.64% CUF and GSPV plant has 17.46% CUF. Therefore, FSPV plant has 1.18% more CUF than GSPV plant. CUF measures the efficiency with which a solar power plant utilizes its capacity over a year.

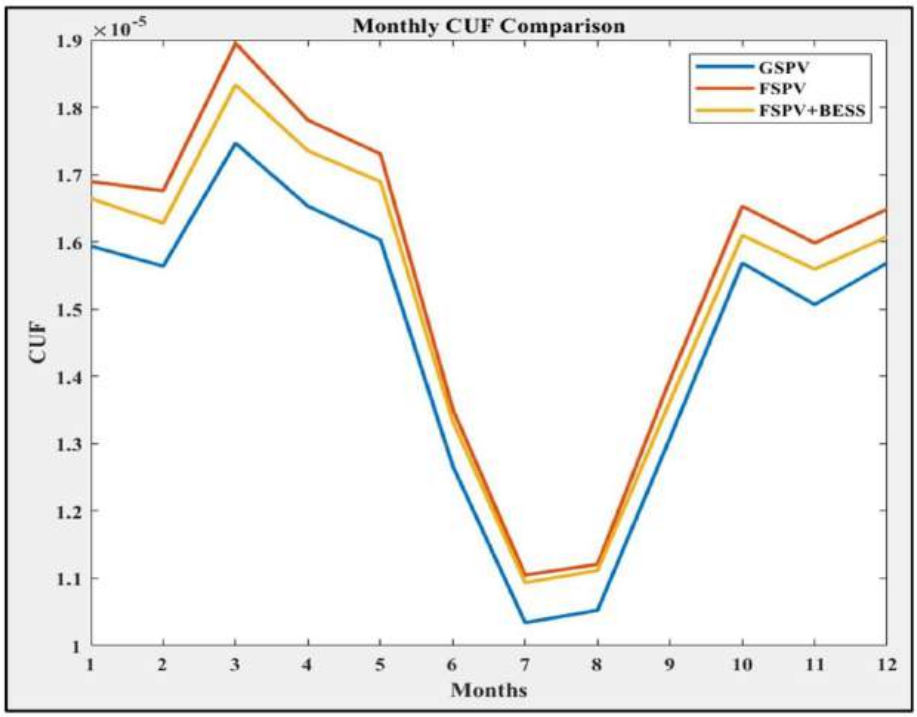

Fig. 4.3: Monthly capacity utilisation factor of GSPV, FSPV, and FSPV+BESS

Table 4.3: Comparative analysis of Technical Parameters

Sr. No.	Parameter	GSPV	FSPV	FSPV+BESS
1.	Module temperature (°C)	63.245	48.9178	48.9178
2.	Annual energy yield (MWh)	7.651	8.168	8.168
3.	PR (in %)	77.2	82.3	80.5
4.	CUF (in %)	17.4658	18.6438	18.2352
5.	Power loss due to temperature	-13.68	-8.90	-8.90
6.	Yf (kWh/kWp/day)	4.19	4.48	4.38
7.	Lc (kWh/kWp/day)	1.09	0.8	0.8
8.	Ls (kWh/kWp/day)	0.15	0.16	0.26
9.	CO_2 emission /savings (tCO_2/year)	176.6	189.2	188.8

4.5.2. Economic parameters and performance of the FSPV plant at Ambazari Lake

Table 4.4. shows the comparative analysis of economic parameters. FSPV plants have higher installation costs than GSPV plants as the costs of floating structure design, anchoring, and the mooring system are added. In the FSPV plant with BESS, the installation cost is higher due to the additional expense of the batteries, making it more expensive than the standard FSPV plant. The cost of BESS depends on its rating. 6 Rs. Per unit is the cost added in FSPV for the battery storage system [28]. Improving installation efficiency, optimizing design, using cost-effective anchoring and mooring, proper maintenance, optimized water body use, giving incentives and subsidies, etc., these can help in reducing the cost of the FSPV plant.

GSPV plant payback period is 5 months more than the FSPV plant payback period. However, the FSPV plant offers an ROI of 125.8%, indicating a 10.5% higher return compared to the GSPV plant. The ROI for an FSPV plant with a Battery Energy Storage System (BESS) is 72.5%. Additionally, the 5 kW FSPV plant's Levelized Cost of Energy (LCOE) and Net Present Value (NPV) are both lower and higher than those of the GSPV plant, respectively. The positive NPV highlights the project's profitability. The LCOE for the

FSPV plant is 8.95% less than that of the GSPV plant. In making a comparison, the land cost of GSPV plant is not considered.

Table 4.4: Comparative analysis of Economic Parameters

Sr. No.	Parameter	GSPV	FSPV	FSPV+BESS
1.	Total Installation Cost	Rs.260300	Rs.306400	Rs.336400
2.	LCOE	3.383 Rs / kWh	3.080 Rs / kWh	3.734 Rs / kWh
3.	Payback period	11 years	10.6 years	13.3 years
4.	NPV	Rs. 300095.26	Rs. 385419.43	Rs. 243983.77
5.	ROI	115.3%	125.8%	72.5%

4.5.3. FSPV with BESS

Table 4.5. shows the monthly energy stored in the battery energy storage system. Fig.4.4 represents the contribution of BESS during peak shaving using PVsyst software. It is assumed that battery is charged in clear sky condition (not partial shading). A FSPV with BESS is designed to reduce grid electricity usage, manage peak demand, and provide backup power during outages for electricity consumers [14]. Yearly the FSPV plant is generating 8.17 MWh of energy out of which as shown in Fig.4.5. (Sankey diagram) 15.5 % of energy is stored in BESS and 84.5% of energy is directly injected into the grid. Therefore, 15.5 % of energy can be used when in need. Thus, 7.99 MWh of energy is injected into the grid.

Integrating a Battery Energy Storage System (BESS) with a Floating Solar Photovoltaic (FSPV) plant enables the storage of surplus energy produced during peak sunlight hours, which can then be utilized during periods of lower solar output or increased demand. This helps to stabilize the energy supply and supports grid balance. By discharging stored energy during peak demand, BESS reduces dependency on grid power, which can lead to potential savings on energy costs. But it requires additional infrastructure. Further battery life is short.

- A battery energy storage system can be installed

i. Near the inverter, this will minimize the distance the electricity has to travel and reduce losses.

ii. Onshore, where space and cooling are readily available.

The lithium-ion battery is used as it has a long life, charges quickly, is lightweight, has low pollution, low self-discharging, and is recyclable, as given in Table 4.5.

Table 4.5: Monthly energy stored in 5 kWp FSPV with BESS

Months	Energy stored in the battery (in MWh)
Jan	0.123
Feb	0.134
Mar	0.149
Apr	0.126
May	0.098
Jun	0.029
Jul	0.028
Aug	0.018
Sep	0.085
Oct	0.126
Nov	0.108
Dec	0.150
Yearly	**1.131**

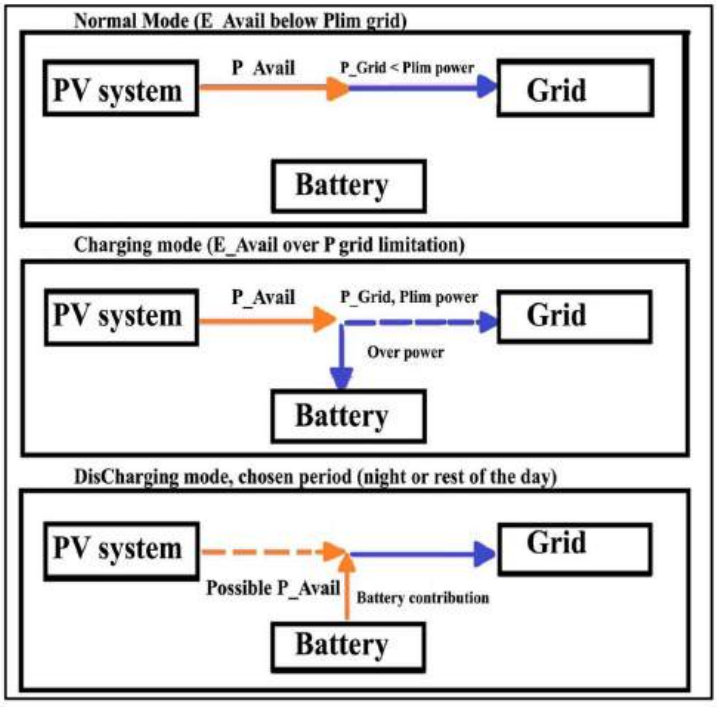

Fig. 4.4: Contribution of Battery Energy Storage System

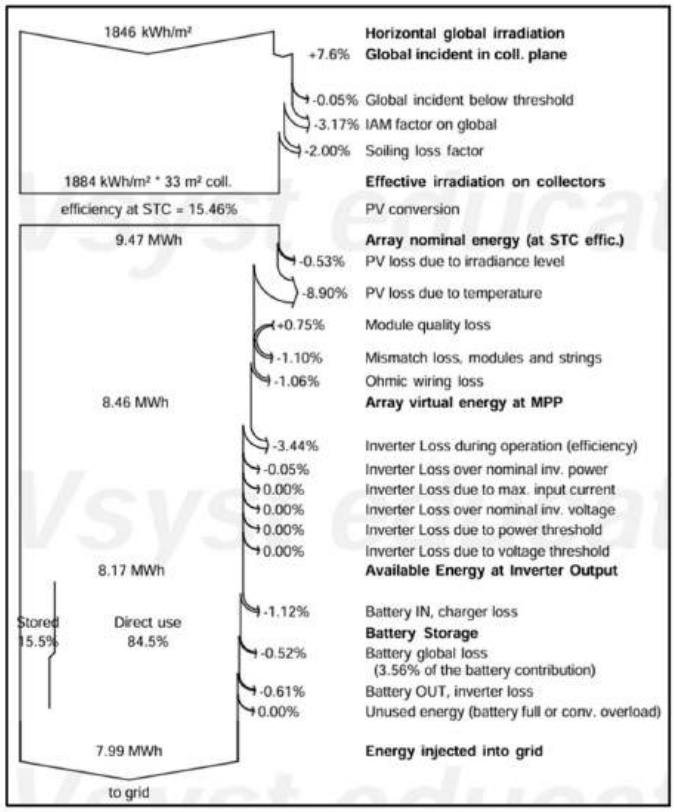

Fig. 4.5: Sankey Diagram for FSPV with BESS

4.5. Conclusion

The FSPV plants contribute to generate clean and renewable energy. The advantages of the FSPV plant over the GSPV plant are seen like low module temperature because of the cooling effect of the water, more energy production than GSPV plant. If BESS is added to FSPV plant then it can store the energy. Technical analysis shows that CUF, PR are more of a FSPV plant than GSPV. Evaporation rate can be reduced by the FSPV plant by placing the solar panels on the water body surface. It curtails about 189.2 tonnes of CO_2 emission over its lifetime which is 12.6 more tonnes of CO_2 emission than the GSPV plant. Economic analysis shows that LCOE of 5 kW FSPV is 3.080 Rs /kWh which needs Rs. 306400 for installation and with payback year of 10.6 years, whereas LCOE of 5kW FSPV with BESS is 3.734 Rs/kWh which needs Rs.336400 for installation with payback of 13.3 years. FSPV with BESS stores 15.5% more energy which is 1.131 MWh. FSPV with BESS gives energy reliability, enhances energy efficiency, etc. Overall, it can enhance the benefits of solar energy and improve energy management.

CHAPTER 5: COMPARATIVE ANALYSIS OF THE PROPOSED FSPV PLANT WITH DIFFERENT CAPACITY.

5.1 Introduction

This chapter presents a comprehensive comparative analysis of technical and economic parameters obtained using MATLAB and PVsyst software. The analysis focuses on two scales of floating solar photovoltaic (FSPV) systems: a proposed 5 kWp plant and an already installed 5MW plant at Ambazari Lake. The outputs are then systematically compared with the corresponding results obtained from PVsyst simulations to evaluate consistency and performance. To analyze the economic viability of the project in detail for the proposed 5kWp FSPV plant economic analysis is done for different cases.

5.2 Techno-Economic analysis of 5MW FSPV plant.

5.2.1. Site details and Meteorological data

The site details and meteorological data used for the analysis are the same as those provided earlier in the site details section of Chapter 2 and in Table 2.1.

5.2.2. FSPV system layout

The configuration of PV modules in series and parallel can be determined using the formulas provided below. The total number of PV modules is calculated by dividing the total capacity of the PV plant by the rated power of an individual module. The number of panels in a single string is derived by dividing the inverter's voltage rating by the maximum voltage of a solar module. Subsequently, the number of strings is obtained by dividing the total number of PV modules by the number of modules per string.

$$\textbf{\textit{Total No. of PV modules}} = \frac{\textbf{\textit{Total PV plant capacity}}}{\textbf{\textit{Rated power of PV module}}} \tag{5.1}$$

$$= \frac{5*10^6\ W}{250\ W} = \mathbf{20000}$$

$$No.of\ PV\ module\ in\ String\ =\ \frac{Max.Voltage\ of\ inverter}{Max.voltage\ of\ solar\ module} \quad (5.2)$$

$$= \frac{300}{28.9} = \mathbf{10.3 \sim 10}$$

$$No.of\ strings\ in\ parallel\ =\ \frac{Total\ no.of\ PV\ modules}{No.of\ PV\ modules\ in\ string} \quad (5.3)$$

$$= \frac{20000}{10} = \mathbf{2000}$$

Calculations showed that the FSPV system consists of 20000 PV modules and 1000 inverters. It has 2000 strings, each consisting of 10 modules in series. Table 5.1 shows the specifications of the PV modules and Inverters.

Table 5.1: PV Module and Inverter Specification

Manufacturer	Generic
PV module model	Poly 250Wp 60 cells
DC Power rating	4.8 kW
AC Power rating	4.2 kW
PV module rating	250 W
Total no. of PV modules	20000
No. of modules in string	10
No. of strings	2000
Inverter model	4.2 kW
No. of inverters	1000

5.2.3. Cost estimation of 5MW FSPV plant

Table 5.2 represents the breakdown of the total cost involved in the proposed 5MWp FSPV plant. The total cost involved is 26,03,00,000 for the 5MW FSPV system at Ambazari Lake.

Table 5.2: Cost Estimation of proposed 5MW FSPV plant

Sr. No.	Item	Quantity (in units)	Cost (INR)	Total Cost (INR)
1.	PV Modules: (Poly 250 Wp 60 Cells)	20000	5,247.50	10,49,50,000.00
2.	Support for Module	20000	2,100	4,20,00,000.00
3.	Inverter	1000	25,200	2,52,00,000.00
4.	Other Components (Accessories, design, construction, testing, and commission)	1	8,81,50,000	8,81,50,000.00
	Total			**26,03,00,000.00**

5.3 Comparative analysis of 5kWp and 5MW FSPV plant- Simulation Results and Discussions

5.3.1. Technical parameter analysis

Table 5.4 presents a comparative overview of technical analysis for floating solar photovoltaic (FSPV) systems of two different capacities: 5 kW and 5 MW. The module temperature remains same for the 5 kW & 5MW plant, i.e., 30.43°C. The annual energy yield of the 5 MW system is 7752.4 MWh, which is approximately 94,885% more than the 8.168 MWh generated by the 5 kW system, primarily due to the significantly larger system capacity. The performance ratio (PR) of the 5 MW plant is 1.21% higher than that of the 5 kW plant, indicating more efficient energy conversion in the larger system. The capacity utilization factor (CUF) for the 5 MW system is also 8.15% higher, at 20.37%, compared to 18.64% for the 5 kW system.

In terms of losses, power loss due to temperature is lower for the 5 MW plant at -7.6%, which is 1.3% less than the 5 kW plant. System losses of the 5 MW plant performs better with lower collection loss (Lc) at 0.71 kWh/kWp/day, which is 11.25% lower than the 5 kW plant. Likewise, system loss (Ls) in the 5 MW plant is 0.15 kWh/kWp/day, which is 6.25% less than the 0.16 value for the 5 kW system. 5MWp plant will have more inverter losses than that of 5kWp plant because it will require more accessories than the 5kWp plant.CO_2 savings in the 5 MW plant are 181405.3 tCO_2/year, emphasizing the scalability and environmental impact of larger systems. Table 5.3 shows the monthly energy generated by the array and

Performance Ratio (PR) of MW FSPV plant. Fig 5.1 represents the comparative Capital Utilization Factor (CUF) of 5kW and 5MW, FSPV and GSPV plant.

Table 5.3: Technical parameters of 5MW FSPV plant

Month	E_array (MWh)	PR
Jan	709.5	0.851
Feb	710.0	0.838
Mar	812.5	0.821
Apr	812.3	0.813
May	779.3	0.807
Jun	581.3	0.826
Jul	468.2	0.833
Aug	486.4	0.842
Sep	602.3	0.832
Oct	701.0	0.831
Nov	682.4	0.842
Dec	685.8	0.848
Yearly	**8031.1**	**0.831**

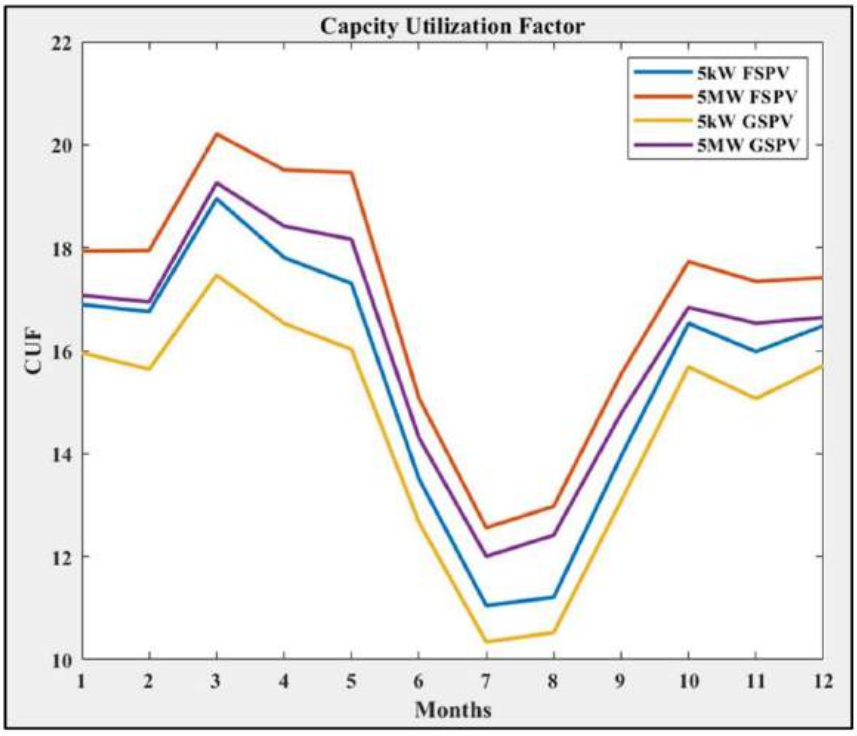

Fig. 5.1: Capital Utilization Factor (CUF) of 5kW and 5MW, FSPV and GSPV plant.

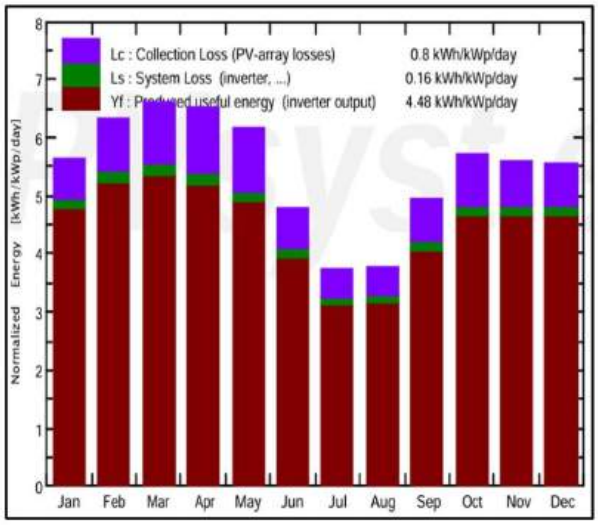
Lc : Collection Loss (PV-array losses) 0.8 kWh/kWp/day
Ls : System Loss (inverter, ...) 0.16 kWh/kWp/day
Yf : Produced useful energy (inverter output) 4.48 kWh/kWp/day
Normalized Energy [kWh/kWp/day]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Fig. 5.2: Normalized Performance Index of 5kW FSPV plant

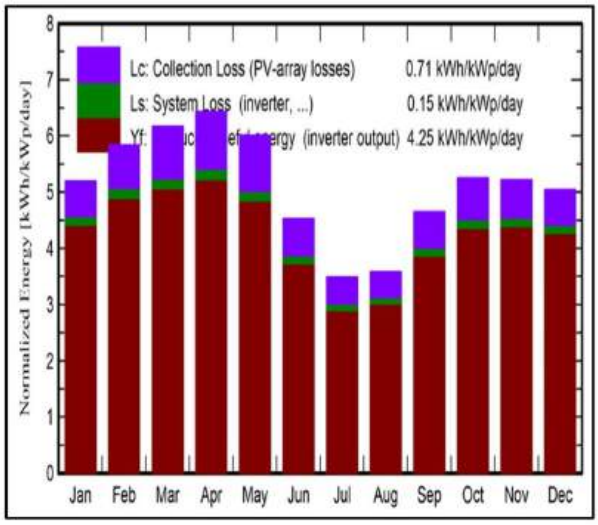
Lc: Collection Loss (PV-array losses) 0.71 kWh/kWp/day
Ls: System Loss (inverter, ...) 0.15 kWh/kWp/day
Yf: ...ergy (inverter output) 4.25 kWh/kWp/day
Normalized Energy [kWh/kWp/day]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Fig. 5.3: Normalized Performance Index of 5MW FSPV plant

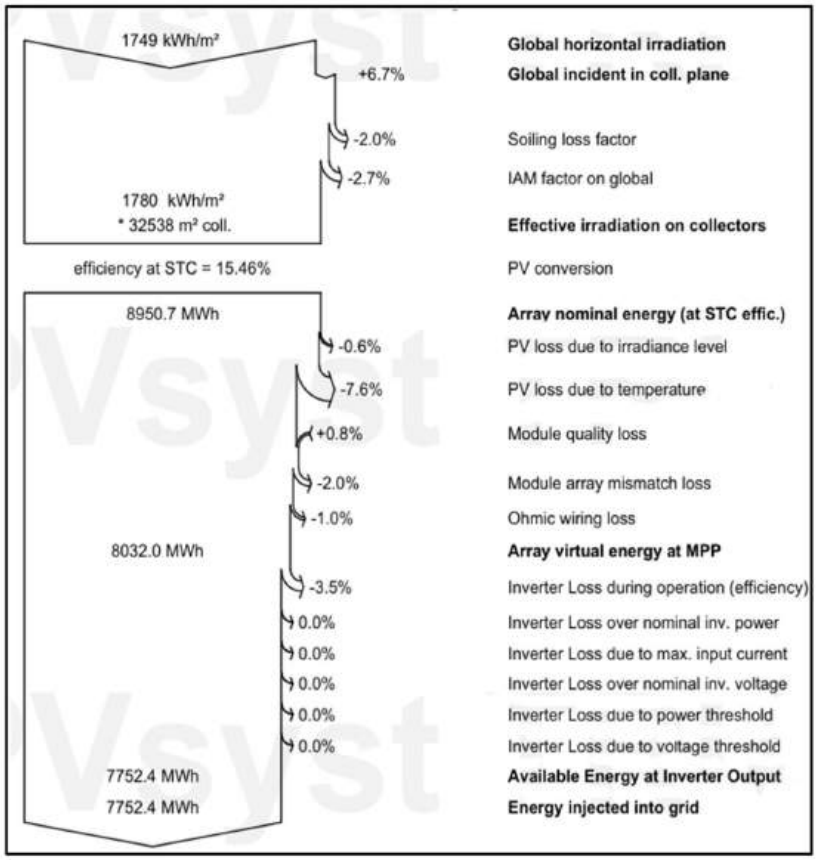

Fig 5.4: Sankey Diagram for proposed 5MW FSPV system

Fig 5.2 and 5.3 shows the Normalized Performance Index for 5kW and 5MW FSPV plant. Fig 5.4 shows the flow of energy from 5MW FSPV plant to the grid.

Table 5.4: Technical parameters of 5kW and 5MW FSPV plant.

Parameter	5 kW FSPV plant	5 MW FSPV plant
Module temperature (°C)	30.43	30.43
Annual energy yield (MWh)	8.168	7752.4
PR (in %)	82.3	83.1
CUF (in %)	18.64	20.37
Power loss due to temperature	-8.90	-7.6
Yf (kWh/kWp/day)	4.48	4.25
Lc (kWh/kWp/day)	0.8	0.71
Ls (kWh/kWp/day)	0.16	0.15
CO_2 emission /savings (tCO_2/year)	189.2	181405.3
Area Covered (sq meters)	50	50,000
Water Saved (Liters)	56,250	5,62,50,000

A 5 kW FSPV system occupies approximately 50 m^2, covering only 0.00193% of the lake's surface area (2.59 km^2), while a 5 MW system spans about 50,000 m^2, which is 1.93% of the total lake area. Despite this modest coverage, the water conservation potential is substantial. Due to the reduction in surface evaporation: estimated at 75% on the covered area, a 5 kW system can save nearly 56,250 liters of water, whereas a 5 MW installation could prevent the loss of approximately 56.25 million liters, contributing meaningfully to water resource sustainability in the region.

5.3.2. Economic Analysis

Table 5.5 shows the economic parameters of the proposed Floating Solar Photovoltaic (FSPV) plants with capacities of 5 kW and 5 MW. The total installation cost for the 5 kW system is ₹3,06,400, whereas the 5 MW system requires a significantly higher investment of ₹26,03,00,000.

Table 5.5: Economic parameters of proposed FSPV plant

Parameter	5kW FSPV plant	5MW FSPV plant
Total Installation Cost (in Rs.)	3,06,400	26,03,00,000
Levelized Cost of Electricity (LCOE) (in Rs / kWh)	3.080	2.234
Payback period (in years)	10.6	7.2
Net Present Value (NPV) (in Rs.)	3,85,419.43	27,28,08,995.28
Return on Investment (ROI) (in %)	125.8	149.7

The Levelized Cost of Electricity (LCOE) decreases with scale, from ₹3.080/kWh for the 5 kW plant to ₹2.234/kWh for the 5 MW plant, indicating improved cost-efficiency in larger installations. Similarly, the payback period is shorter for the larger system at 7.2 years, compared to 10.6 years for the smaller plant. The Net Present Value (NPV) further reflects the economic advantage of scaling up, with the 5 MW plant yielding ₹27,28,08,995.28, a substantial increase over the ₹3,85,419.43 achieved by the 5 kW system. Additionally, the Return on Investment (ROI) is higher for the 5 MW plant at 149.7%, compared to 125.8% for the 5 kW plant. This parameter collectively highlights the enhanced financial viability and attractiveness of large-scale FSPV projects. Fig 5.5 and Fig 5.6 shows the Cumulative cashflow of 5kW and 5 MW FSPV plant.

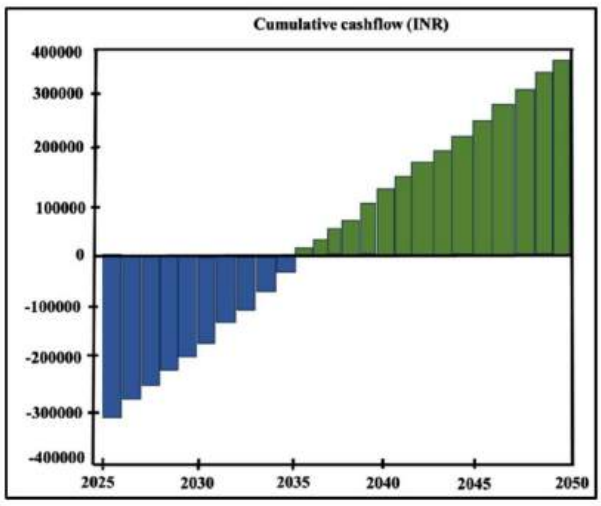

Fig. 5.5: Cumulative cashflow of 5kW FSPV system.

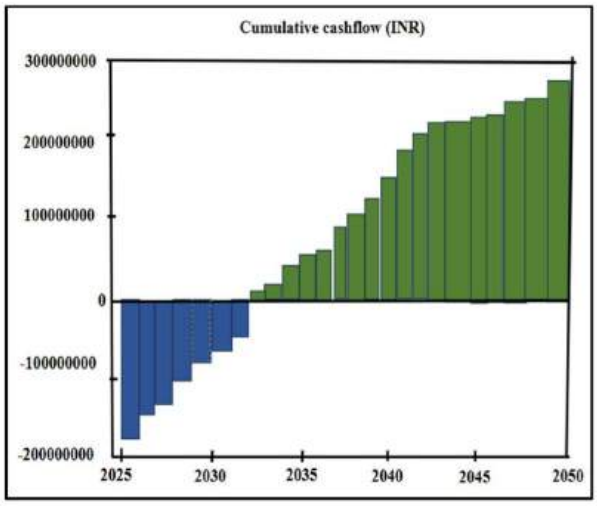

Fig. 5.6: Cumulative cashflow of 5MW FSPV plant.

5.4 Conclusion

In this chapter comparative analysis of the 5kW and 5MW FSPV plant at Ambazari Lake is carried out. Based on the technical and economic analysis of the proposed 5 kW and 5 MW Floating Solar Photovoltaic (FSPV) systems, it is evident that the scalability of such installations significantly enhances both performance and financial viability. The 5 MW FSPV plant exhibits superior capacity utilization (CUF of 20.37%) and performance ratio (PR of 83.1%) compared to the 5 kW system, while also achieving a lower Levelized Cost of Electricity (LCOE) of ₹2.234/kWh and a shorter payback period of 7.2 years. Moreover, the 5 MW plant demonstrates substantial environmental and resource benefits, including an estimated annual CO_2 savings of 1, 81,405.3 tons and water conservation exceeding 5.6 million liters. The economic returns are also favorable, with a higher ROI of 149.7% and a significantly greater Net Present Value. These findings collectively highlight the technical feasibility and economic attractiveness of deploying large-scale FSPV systems, making them a promising solution for sustainable energy generation.

CHAPTER 6: GENERAL CONCLUSIONS

6.1. General Conclusions

The analysis demonstrates that FSPV systems, especially with tracking mechanisms and optional BESS integration, offer a balanced combination of high energy yield, enhanced performance metrics, and environmental benefits. Although the capital and life cycle costs are marginally higher than traditional systems, the reduced LCOE, shorter payback period (especially in large-scale systems), and improved ROI make them economically attractive. The scalability from a 5 kWp to a 5 MW plant shows considerable improvement in performance metrics, CUF of 20.37% and PR of 83.1%, and a significant drop in LCOE to Rs.2.234/kWh with a reduced payback of just 7.2 years, confirming the financial feasibility of large-scale deployment.

The findings emphasize that floating solar installations, especially when implemented on idle water bodies like Ambazari Lake, represent an environmentally sustainable and resource-conscious method for producing renewable energy. Large-scale FSPV plants not only offer greater energy independence but also contribute substantially to environmental preservation through CO_2 mitigation and water conservation. This research establishes a solid foundation for future studies and implementations of FSPV systems in similar geographies, promoting them as a viable and impactful component of India's renewable energy roadmap.

6.2. Significant contributions

This thesis presents a site-specific techno-economic analysis of FSPV systems deployed on inland water bodies, using Ambazari Lake in Nagpur as a case study. It uniquely combines technical performance assessment with financial evaluation by analyzing different configurations, including fixed, SAT, and TAT FSPV systems, as well as integration with Battery Energy Storage Systems (BESS). The study uses dual simulation tools PVWatts and PVsyst, to validate performance metrics such as energy yield, capacity utilization factor, and performance ratio, while also quantifying environmental benefits like CO_2 emission reduction and evaporation savings. The thesis advances understanding of economic performance by

calculating location-specific Levelized Cost of Electricity, payback duration, and Return on Investment for each floating solar system design. Additionally, the inclusion of BESS shows how energy reliability and storage capacity can be enhanced in floating setups. The final part of the study scales the system design from a 5 kWp small-scale to a proposed 5 MW utility-scale FSPV plant, demonstrating how scalability dramatically improves technical performance and economic returns, making large-scale floating solar a viable and sustainable solution for energy generation in water-rich regions.

6.3. Future Scope

Future research will focus on conducting a techno-economic assessment of a hybrid system combining a floating solar PV setup with a hydroelectric power plant.

REFERENCES

[1] Rosa-Clot and G. M. Tina, Chapter on "The Floating PV Plant," in Submerged and Floating Photovoltaic Systems: Elsevier, Inc., 2018, pp 89-136

[2] G. M. Masters, Chapter on "The solar resource," in Renewable and Efficient Electric Power Systems: John Wiley & Sons, Inc., 2013, pp 445-450.

[3] Floating PV in India Report, German Cooperation, GIZ, January 2024.

[4] Where Sun Meets Water, Floating Solar Market Report, World Bank Group, and SERIS, Singapore,2019

[5] Niccolai, F. Grimaccia, G. Di Lorenzo, R. Araneo, F. Ughi and M. Polenghi, "A Review of Floating PV Systems with a Techno-Economic Analysis," proceedings of IEEE journal of photovoltaics, Vol.. 14, no.1 January 2024, doi: https://doi.org/10.1109/JPHOTOV.2023.3319601

[6] Madhubabu and G V S. K Rao," Review of technology involved in floating solar PV system," proceedings of IEEE International Conference on Communication and Electronics Systems (ICCES), doi: https://doi.org/10.1109/ICCES51350.2021.9489048

[7] S.S. Gurfude, C. Bhavitha, D. Tanusha, D. Mounika, S. P. G. Kake, M S. Sudha and P.S. Kulkarni, " Techno-economic Analysis of 1 MWp Floating Solar PV Plant," proceedings of IEEE International Conference on Smart Technologies for Power, Energy and Control (STPEC),doi: https://doi.org/10.1109/STPEC49749.2020.9297740

[8] Patil, G. Mamatha and P. S. Kulkarni, "Techno-Economic Analysis of proposed 10kWp Floating Solar Plant at Koyana Dam, Maharashtra, India," proceedings of IEEE International Conference on Power Electronics & IoT Applications in Renewable Energy and Its Control (PARC), doi: https://doi.org/10.1109/PARC52418.2022.9726247

[9] B.Snehith and P.S Kulkarni, "Techno-Economic analysis of 10 MWP floating solar PV plant at Nagarjuna Sagar, Telangana, India: Part-1," proceedings of IEEE

International Conference on Communication, Control and Information Sciences (ICCISc), doi: https://doi.org/10.1109/ICCISc52257.2021.9484867

[10] Snehith and P.S Kulkarni, "Techno-Economic analysis of 10 MWP floating solar PV plant at Nagarjuna Sagar, Telangana, India: Part-2," proceedings of IEEE International Conference on Communication, Control and Information Sciences (ICCISc),doi: https://doi.org/10.1109/ICCISc52257.2021.9484963.

[11] G. Mamatha and P.S. Kulkarni, "Feasibility analysis of Floating Solar Photovoltaic Plant at Srisailam in Andhra Pradesh, India", proceedings of IEEE International Conference on Smart Technologies for Power, Energy and Control (STPEC), doi: https://doi.org/10.1109/STPEC52385.2021.9718627

[12] Mittal, B. K. Saxena and K. V. S. Rao, "Comparison of Floating Photovoltaic Plant with Solar Photovoltaic Plant for Energy Generation at Jodhpur in India," proceedings of IEEE International Conference on Technological Advancements in Power and Energy (TAP Energy), doi: https://doi.org/10.1109/TAPENERGY.2017.8397348

[13] U. Ramzan and M. Jamil, "Comparative Analysis of Floating Solar Photovoltaic and Land Based Photovoltaic Plant," proceedings of IEEE International Conference on Silchar Subsection Conference (SILCON), doi: https://doi.org/10.1109/SILCON55242.2022.10028831

[14] D. Boruah and S. S. Chandel, "Techno-economic feasibility analysis of a commercial grid-connected photovoltaic plant with battery energy storage-achieving a net zero energy system," proceedings of Journal of Energy Storage, Elsevier, vol.77, 2024, doi: https://doi.org/10.1016/j.est.2023.109984.

[15] Z. Yang and Z. Xiao, "A Review of the Sustainable Development of Solar Photovoltaic Tracking System Technology", MDPI, Energies 2023, 16, 7768, doi: https://doi.org/10.3390/en16237768

[16] R. Abhinav, R. Adithya, V. Anson and M. Harigovind, "Performance Analysis of Single Axis Tracking and Floating Solar Panel for Domestic usage," proceeding of Asia Pacific Power & Energy Engineering Conference (APPEEC),2021, doi: 10.1109/APPEEC50844.2021.9687778

[17] S.S. Gurfude and P.S. Kulkarni, "Energy Yield of Tracking Type Floating Solar PV plant," proceeding of National Power Electronics Conference (NPEC), Tiruchirapalli, India, 2019,doi: https://doi.org/10.1109/NPEC47332.2019.9034846.

[18] Hammoumi, S. Chtita, S. Motahhir and A. Ghzizal, "Solar PV energy: From material to use, and the most commonly used techniques to maximize the power output of PV systems: A focus on solar tracker and floating solar panels", Elsevier, Energy Report 8, 2022, doi: https://doi.org/10.1016/j.egyr.2022.09.054

[19] Avasthi, R. Garg and P. Mahajan, " Optimizing energy harvesting: a comprehensive analysis of tracking technologies in a 2MWp floating solar photovoltaic system", Springer, 2024, doi: https://doi.org/10.1007/s00202-024-02780-3

[20] M. Rifansyah and D. F. Hakam,"Techno economic study of floating photovoltaic project in Indonesia using RETscreen", Elsevier, Journal of Cleaner Energy Systems,2024,doi: https://doi.org/10.1016/j.cles.2024.100155.

[21] H. Jee, Y. Noh, M. Kim, and J. Lee, "Comparing the Performance of Pivotless Tracking and Fixed-Type Floating Solar Power Systems," MDPI Journals, Applied Sciences 2022, Volume 12, Issue 24, doi: https://doi.org/10.3390/app122412926

[22] Akgul, M. S. Ozyazici and M. F. Hasoglu, "Estimation of optimal tilt angles and solar radiation collected by fixed and tracking solar panels for the Mediterranean region, Turkey", Indian Journal of Physics, IACS 2024,doi: https://doi.org/10.1007/s12648-023-02894-7

[23] M. A. P. Jara, C. V. Figueroa, M. R. Mero and C. R. Casas, "Performance Comparison Between Fixed And Dual-Axis Sun Tracking Photovoltaic Panels With An IoT Monitoring System In The Coastal Region Of Ecuador", MDPI Journal, Sustainability 2022,doi: . https://doi.org/ 10.3390/su14031696

[24] R. Cazzaniga, M. Cicu, M. Rosa-Clot, P. Rosa-Clot, G. M. Tina and C. Ventura, "Floating photovoltaic plants: Performance analysis and design solutions," Journal Renewable and Sustainable Energy Reviews, Elsevier, vol.18, pp.1730-1741, 2018, doi: https://doi.org/10.1016/j.rser.2017.05.269

[25] Ghigo, E. Faraggiana, M. Sirigu, G. Mattiazzo and G. Bracco, "Design and Analysis of a Floating Photovoltaic System for Offshore Installation: The Case Study of

Lampedusa," proceedings of article MDPI, Energies, doi: https://doi.org/10.3390/en15238804

[26] B. H. Khan and Md. N. Hasan, "Performance analysis of floating photovoltaic system with different types of battery energy storage systems," Journal of Renewable Energy, Elsevier, vol. 168, pp. 654–668, 2021, doi: https://doi.org/10.1016/j.renene.2020.12.052.

[27] PVsyst 6.88 premium version. [online] https://www.pvsyst.com/download-pvsyst/.

[28] Renewable sector published report, JMK Research and Analytics,2024.

[29] International Renewable Energy Agency (IRENA), 2024, https://www.irena.org

[30] Annual Floating Solar Additions to Top 6 GW by 2031, Wood Mackenzie, 2023.

[31] *Renewables 2023: Market Analysis and Forecast to 2028*, International Energy Agency (IEA), 2023.

[32] NTPC Projects, https://www.ntpc.co.in

[33] Rewa Ultra Mega Solar Ltd (RUMSL), https://www.rumsl.com

[34] Madhya Pradesh Urja Vikas Nigam Ltd., https://www.mpuvn.gov.in

[35] Chandigarh Renewable Energy and Science & Technology Promotion Society (CREST), https://www.crestchd.org.in

[36] Greater Visakhapatnam Municipal Corporation (GVMC), https://gvmc.ap.gov.in

[37] India Energy, https://www.indiaenergyportal.org

[38] National Institution for Transforming India (NITI), https://www.niti.gov.in

[39] Ministry of New and Renewable Energy (MNRE), https://www.mnre.gov.in

[40] Central Electricity Authority (CEA), https://cea.nic.in

[41] National Power Portal (NPP), https://npp.gov.in